Report of NAVOCEANO Flight

over Lake Michigan

17-21 October 1966

Scientific personnel:

J. Wilkerson M. Brattnick	NAVOCEANO
E. Stoermer V. Noble	University of Michigan
R. Ragotzkie K. Menón N. Smith	University of Wisconsin

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FOREWORD

The proposal for the flight over Lake Michigan was initiated by the U.S. Naval Oceanographic Office. During the early phases of the planning for this flight, the Great Lakes Research Division agreed to publish the data report of the results of the flight.

The Great Lakes Research Division of the University of Michigan and the Meteorology Department of the University of Wisconsin participated in the flight operations. The U.S. Lake Survey provided support operations in Toledo, Ohio, for the Lake Erie portion of the flight, and the U.S. Coast Guard provided a vessel, the RARITAN, for surface support during the Lake Michigan operation.

The Universities of Michigan and Wisconsin are grateful for the opportunity to participate in the Lake Michigan mission, and would like to express their very great appreciation to Mr. John Ropek of the Naval Oceanographic Office, who proposed the flight, and to Plane Commander James Odee, LCDR, U.S. Navy, his flight crew from EL COYOTE, and its civilian staff under the scientific direction of John Wilkerson for the execution of the flight.

Partial support for the participation in the flight mission and the preparation of the data report was provided by the Atmospheric Sciences Section, National Science Foundation, NSF Grant GA-524; NSF GB-4982; and by the Federal Water Pollution Control Administration Research Grants WP-01067 ESEA, and WP-00311.

Vincent E. Noble

INTRODUCTION

The proposal for the flight mission over Lake Michigan was the result of several conversations with the Navy, and was initiated by the Naval Oceanographic Office, Anti-Submarine Warfare Environmental Prediction Services (ASWEPS). The aircraft, a Navy Super Constellation, is an oceanographic research aircraft under technical control of the Naval Oceanographic Office with operational control assigned to Air Development Squadron Eight (formerly the Oceanographic Air Survey Unit), Patuxent River Naval Air Station. The aircraft was named EL COYOTE.

The flight mission was planned as a pilot experiment over fresh water, both to demonstrate the capabilities of the airborne instrumentation as research facilities and to provide calibration information for the application of the instrumentation to other than completely marine environments. Also, the mission was to demonstrate the potential of airborne oceanographic research on the Great Lakes and to make available in public interest Navy's advanced aerial oceanographic capabilities. The instrumentation used in this flight mission was: two infrared radiation thermometers (Barnes Model 14-320 Airborne Radiation Thermometer (ART) which is the standard aircraft instrument, and the Barnes Model IT-3 which was installed for one day of the mission by the University of Wisconsin); wave profiling radar; meteorological set (AN/AMQ-17) for the measurement of temperature, pressure, and relative humidity; two radiometers for the measurement of incoming and reflected solar radiation; a CA-8 aerial camera for precision photography; and four hand-held cameras using different films operated by a Navy photographer and University of Michigan personnel. Table 1 presents a summary of the instrument characteristics.

Surface control data and calibration reference points were provided by the U.S. Lake Survey (one tower station in Lake Erie, and two in Lake

TABLE 1. Instrument Characteristics

Instrument	Measurement	Measurement Technique	Recorder Output	Range	Accuracy
Infrared radiation thermometer, Model 14-320, Barnes Engineering Company	Sea surface temperature	Radiation in the 8-13 micron region is detected by a thermistor bolometer Energy received is proportional to temperature. Electronic processing translates energy measurement into temperature reading.	Analog	-2°C to +35°C	±0.2°C (Laboratory)
Infrared radiation thermometer, Model IT-3					
Wave profiling radar Wave height indicator AMACOM, Division of Litton Systems	Ocean wave height	Precise radar ranging with a narrow vertical beam provides instantaneous distance to a spot on the ocean surface directly beneath the aircraft. Vertical aircraft motion is monitored and corrected through accelerometers and integrators.	Analog	2 ft to 50 ft	±10% of actual wave heights or ±6 inches whichever is greater
Meteorological Set (AN/AMQ-17), Bendix Friez Corp.	Air temperature, Relative Humidity, Pressure	Bridge network with following elements in the balance circuit: Temp. - Platinum wire resistor Humidity - Carbon coated resistor Pressure - Bellows mechanically linked to potentiometer	Analog and digital	-50°C to 49°C 0 to 90% 50 to 1050 mb	5% 5% 5 mb
Radiometer (Spectral Bandpass--0-2.8 microns) .3-2.8, Eppley Lab., Inc.	Solar Radiation Eppley Laboratory	Radiation incident upon the thermocouples of the radiometer generates voltage proportional to intensity of solar radiation	Analog	0 to 2 $gm/cm^2/sec$	3% (in 20°C to -20°C ambient temperature range)
Mapping Camera, CA-8	Ektachrome	Precision Cartographic	Strip photography		
Camera 1	IR-Aero-Ektachrome	35 mm hand-held photography of various features of interest			
Camera 2	High-Speed Ektachrome				
Camera 3	Kodachrome				
Camera 4	Plus-X Pan with "A" filter				

Michigan); the U.S. Coast Guard Cutter RARITAN (operating out of Milwaukee on Lake Michigan); the University of Wisconsin (surface temperature calibration on Lake Mendota); and two University of Michigan ships (R/V MYSIS operating out of South Haven, and R/V INLAND SEAS operating out of Ludington on Lake Michigan).

SUMMARY OF FIELD OPERATIONS

The EL COYOTE left its home base at Patuxent Naval Air Station on the morning of 17 October 1966 and flew over Lake Erie on its way to Ann Arbor. The flight path, shown in Figure 1, was from Erie, Pa., west to Pointe Pelee, Ont., south around the Islands, and then east from Put-In-Bay to Toledo, Ohio, where the aircraft crossed the tower operated by the U.S. Lake Survey. Continuous temperature measurements were made along the flight path, but low winds and sea state prevented meaningful wave measurements.

The aircraft arrived at Willow Run Airport before noon on 17 October, and was briefed as to the reports of heavy northwest winds over Lake Michigan that morning. V. E. Noble and E. F. Stoermer (University of Michigan) boarded the aircraft as it left Willow Run on its way to Truax Field, the base of operations in Madison, Wis. The flight path was planned so that the crossing over Lake Michigan would be in a northwesterly direction from the wave-measuring installation operated by the Lake Survey near Muskegon. Unfortunately, both the wind and waves had diminished before the aircraft reached Lake Michigan, so that again only temperature measurements could be obtained.

After the arrival at Truax, a briefing was held at the Meteorology Department, University of Wisconsin (who acted as local hosts during the mission), by R. A. Ragotzkie, and the IT-3 radiation thermometer was installed in the aircraft by that University.

The aircraft was boarded by N. Smith and K. Menon (University of Wisconsin) upon its departure from Truax on the morning of 18 October for the major portion of the flight program. The aircraft flew over Lake Mendota for an initial temperature calibration and crossed over Lake Michigan on an east heading from Chicago at 1303 Z. Temperature measurements were made from an altitude of 500 ft on 23 east-west transects of the lake from Chicago to Harbor Springs, then north on a "dog-leg" in the Straits region and back down the upper portion of the lake before leaving the lake at 2137 Z for its return to Truax. The flight path is shown in Figure 6. During the flight the winds and waves were again too light for meaningful measurements, a low overcast restricted the light for good photography, and scattered showers threatened to cause serious interference with the temperature measurements and radio communications with the support ships. Fortunately, however, the rain caused little interference with the temperature measurements, and provided an opportunity for a nearly synoptic (8 1/2-hours duration) measurement of the distribution of rainfall over the lake.

The R/V MYSIS departed South Haven along the 5th flight line early in the morning of 18 October and was crossed midlake by the COYOTE. The MYSIS measured water surface temperatures with a thermistor probe towed from a bow-sprit ahead of the ship, water temperatures in an intake line 3 feet below the surface, and made bathythermograph casts every 2 miles along the transect. On 19 October, the MYSIS returned to the east side of the lake by steering a zig-zag course 45° north and south of the flight path of the previous day. Each leg of the zig-zag was 3 miles long. On the return crossing, the MYSIS measured surface temperatures, intake temperatures, and made BT casts at each turn on her course. The temperature transects and dynamic height currents computed from the BT data are given in Figure 12.

The USCGC RARITAN sailed from Milwaukee along the 9th flight line where she was crossed midlake by the COYOTE on 18 October. Surface temperature measurements were made with a thermistor probe, lowered at intervals from deck, both on her way out to the midpoint and on her subsequent return to Milwaukee.

The INLAND SEAS sailed west from Ludington on the 14th flight line, making surface temperature measurements with a towed thermistor probe, intake temperature measurements at a depth of 6 feet, BT casts every 2 miles, dropped Rhodamine B dye markers along her course, and was crossed midlake by the aircraft on 18 October. Unfortunately, the weather and lighting conditions that existed when the aircraft traversed the lake on the flight path prohibited effective photography of the diffusion of the dye markers. On 19 October the SEAS returned to the east side of the lake, steering a zig-zag course of 3-mile legs 45° north and south of the flight path, taking continuous surface and intake temperature measurements and making a BT cast at each turn. On 20 October the SEAS crossed the lake for the third time, heading west in a straight line along the flight path, making surface and intake temperature measurements, and a BT cast every 2 miles. The temperature traces and the dynamic height currents computed from the BT casts are shown in Figure 13.

During the flight of 18 October, a strong thermal gradient was observed that began just off shore near Milwaukee, ran north to the region of Sheboygan, turned northeast to the center of the lake, where it again turned north and ran up the center of the lake. This gradient was very sharp, with the cold water on the west side and the warm water on the east, and was characterized by an abrupt change of temperature of 2°C to 4°C. The temperature gradient zone could be detected visually by the pilots because of the change in water color and a difference in the appearance of the water surface.

The pilots' observations were that it looked like a current.

Since the one-minute average values of the water-surface temperature were continuously being plotted along the flight path, it was possible to have a map of the above temperature gradient by the end of the flight. Therefore, on the night of 18 October, it was possible to inform the SEAS of the full extent of this feature (which only appeared as a singular point along her cruise track), and to instruct her to make a third day of measurements in this region (on 20 October as well as on the 18th and 19th).

On 19 October it was planned to make a flight to photograph and map some selected nearshore features and river plumes that had been observed under the poor lighting conditions of the 18th, and to fly the aircraft along the zone of abrupt temperature change so as to be able to again map the gradient in the same way as the Gulf Stream is mapped. In spite of good weather (and good predictions) at take-off, there was haze and an overcast over the lake that prevented photography. Further, the navigation radar broke down, so that it was not possible to do accurate mapping of the thermal gradient zone, although it appeared to be of the same magnitude and in the same relative position as on the previous day. The flight was cut short.

The remainder of the 19th and all of 20 October were devoted to a debriefing and an exchange of data.

Ship weather reports showed that by 2400 GMT (1900 EST) on 20 October the wind picked up from the south to 16-24 knots. The wind remained southerly 25-32 knots over the entire lake on 21 October. The weather was clear.

The COYOTE took off on 21 October, flew over the beach zone and river plume off Manitowoc for photographic mapping, flew up to the Waugoshance Point area to do photo mapping of some of the reefs, flew down the axis of

the lake on a successful wave profile run, photo mapped a beach region and the river plume at Benton Harbor, and landed at Willow Run. A mechanical difficulty prevented a repeat of the Lake Erie run on the way back to Patuxent.

The Geostrophic current associated with the strong temperature gradient zone, as revealed by the computations from the BT casts made by the INLAND SEAS has been named the Coyote Current.

LAKE ERIE: 17 October 1966

The flight path of the aircraft was from Erie, Pa., west to Point Pelee, Ont., south through the Islands, and east to Toledo. The flight path and uncalibrated average temperature values from the ART are shown in Figure 1. The analog data output from the ART must be corrected for two factors that affect the accuracy of the temperature readings. The first is the variation in temperature of the lens from its temperature at calibration, and the second is the environmental effect due to the moisture in the air column between the aircraft and the sea surface. Pickett* has described the environmental correction term as it is applied in marine measurements. The average values of the uncorrected ART readings are 1°C lower than corresponding bucket temperatures, with a standard deviation of the order of 0.4°C. The data shown in Figure 1 are one-minute averages of the ART output with the lens temperature correction applied. Since no bucket temperatures were taken along the Lake Erie flight path, the moisture profile in the air column over Lake Erie was not known, and the standard deviation for marine ART-bucket comparisons was only 0.4°C, it was deemed appropriate that this correction term be left out in the analysis of the Lake Erie data.

* Pickett, R. L. 1966. Environmental corrections for an airborne radiation thermometer. Proc. 4th Symposium on Remote Sensing of Environment. Univ. Michigan, Infrared Physics Lab., p. 259-262.

The subsequent measurements over Lake Michigan showed that the ART readings were consistently 0.4°C lower than the bucket temperatures. No meaningful wave records were made.

The analog output from the ART has been traced (for better reproduction) and re-scaled with the lens correction applied. No environmental correction has been used and it is presumed that the absolute value of the temperature record is 0.4°C low. This record is shown in Figure 2, along with the corresponding data for incoming solar radiation which is shown in Figure 3.

LAKE MICHIGAN: 17 October 1966

ART radiation temperature recordings were made over Lake Michigan on 17 October while the aircraft was in transit to Truax field. The flight path and one-minute temperature averages (lens correction added, environmental correction omitted) are plotted in Figure 4. Again, it may be presumed that the temperatures are of the order of 0.4°C low. A tracing of the analog ART record is given in Figure 5.

LAKE MICHIGAN: 18 October 1966

The major portion of the flight program was accomplished on 18 October 1966. The flight consisted of 23 east-west transects over the lake, at 10-mile intervals, from Chicago to Harbor Springs; then a "dog-leg" in the Straits region with a final path down the center of the upper portion of the lake. The flight path, with corrected one-minute average temperatures, is plotted in Figure 6. The temperatures for this day have had both the lens correction and an empirical environmental correction applied. From the crossings over the three ships, the MYSIS, RARITAN, and INLAND SEAS, on Transects 5, 9, and 14, respectively, the ART appeared to be reading a consistent 0.4°C below the true temperature. This value is also consistent

with the difference between the ART temperature and the surface temperature measured on Lake Mendota while the aircraft was flying to the Lake Michigan starting point at Chicago. The flight path and ART record from Lake Mendota are shown in Figure 7. The tracing of the ART record has been corrected for lens temperature, but no environmental correction has been applied. The surface temperature check data compiled by the University of Wisconsin are given in Table 2.

Isotherms from the corrected one-minute average temperatures are plotted in Figure 8. Tracings of the corrected ART analog records for the flight transects are shown in Figure 9. As indicated above, the records have been traced as an aid to publication of the report. The noise level in the record is within ±0.05°C and is generally well represented by the width of the traced line.

The incoming solar radiation data are given in Figure 10.

Surface water temperatures measured from the USCGC RARITAN are shown in Figure 11. These temperatures were measured along flight line 9 (43°07'N) from the Wisconsin shore to a station at 43°07'N, 87°00'W. The temperature measured on station at 1603 Z, (1103 EST) served as one of the "ground truth" temperature calibration points for the ART on 18 October 1966.

The surface temperatures and dynamic height currents computed from BT transects made by the MYSIS and the INLAND SEAS are shown in Figures 12 and 13. Figure 13 shows the dynamic height currents and surface temperatures obtained by the INLAND SEAS along the latitude line 43°57.2'N on 18, 19, and 20 October 1966.

The "Coyote Current" associated with the temperature gradient zone appears in the region of 87°W in Figure 13. The strong current shear at 86°45'W on 18 October 1966 may well be indicative of a poor BT cast.

TABLE 2. Surface Temperature Check over Lake Mendota on October 18, 1966.

Time: 15:30 - 16:00 GMT (10:30 - 11:00 CDT)

Location: Between Picnic Point and Maple Bluff

Weather:

Wind: 10 - 15 m.p.h. from S.W.

Water Surface: Rough

LOCATION:

Surface Water	Temp. by Whitney Thermistor Thermometer		A.R.T. Temp. (including lens correction) every 1/4 mile across Lake Mendota
1) 1/4 mile from P.Pt.	13.1°C	1)	11.9
2) 1/2 mile from P.Pt.	13.1°C	2)	12.0
3) 3/4 mile from P.Pt.	13.08°C	3)	12.0
4) 1 mile from P.Pt.	13.08°C	4)	12.0
5) 1 1/4 mile from P.Pt.	13.05°C	5)	12.1
6) 1 1/2 mile from P.Pt.	13.02°C	6)	12.2
		7)	12.1
	13.05°C		12.07°C

Difference between ART and surface measurement in 3 hours = 0.98°C. With 10-15 knots of wind, radiation skin temperature can be expected to be 0.5 to 0.8°C cooler than "bucket" temperature.

METEOROLOGICAL SUMMARY

A synopsis of the Great Lakes Weather Observations made by the Carferries ARTHUR K. ATKINSON, CITY OF MADISON, and S.S. SPARTAN is given in Table 3. The ATKINSON provided a general weather coverage from 15 October through 21 October, while the MADISON and the SPARTAN provided detailed coverage for 18 and 19 October.

<u>General Situation</u> 1300 EST (1800 GMT) 18 October 1966

A low pressure trough extended over central U.S. with an associated surface cold front lying from northern Wisconsin southwest to the pan handle of Texas. The front moved eastward and 24 hours later (1300 EST 19 October) was lying north-south through the lower peninsula of Michigan.

<u>Significant Weather</u>

Light to moderate precipitation existed in advance of the front and was widespread in eastern Wisconsin, across Michigan and into northern Ohio. The rainfall pattern observed by the EL COYOTE on the day of the synoptic flight (18 October) is shown in Figure 14.

The prevailing visibility was 5-7 miles with the reduction due to haze and lowered to 3-5 miles in light to moderate rain.

Sky conditions were generally overcast with occasional breaks in the overcast. Ceilings were 1000 ft above surface and lowered to 500 ft in rain showers. The clouds were reported as stratus and stratocumulus with layers up to 10,000 ft.

The reduction of incoming solar radiation was the most significant weather-related factor for this mission. Normal short wave radiation for 18 October is given in Figure 15, and can be compared to observed values given in Figure 10.

TABLE 3. SHIP WEATHER OBSERVATIONS

Ship: ARTHUR K. ATKINSON

Date	Time	Lat.	Long.	Clouds	Wind	Vis	Wx	Pressure	Waves	Air Temp.	Water Temp.
15 Oct	1700	44.6°W	86.6°W	(6)	20/26	98	02/6	987	19/7	11.7	
15 Oct	1900	44.6	87.6	(8)	20/22	97	15/2	999	21/4	7.8	5.6
16 Oct	1400	45.0	86.5	(7)	35/25	98	16/7	1028	36/5	4.4	7.2
16 Oct	1400	44.4	86.9	8	34/19	99	02/5	1032	35/2	5.6	7.2
17 Oct	0700	44.6	86.7	9	28/15	98	20/5	1028	27/1	5.6	7.2
17 Oct	1400	44.5	86.6	1	32/12	98	02/0	1030	32/2	5.0	5.0
17 Oct	2100	44.5	86.8	2	24/06	99	01/0	1033	32/0	6.7	5.6
18 Oct	1600	44.1	86.3	3	16/22	98	00/5	1032	16/3	7.8	9.4
18 Oct	1700	44.4	86.3	7	17/28	98	03/1	1020	17/3	7.8	9.4
18 Oct	1800	44.3	86.5	9	20/14	98	25/2	1020	17/3	7.8	9.4
18 Oct	1900	44.2	87.0	9	20/14	98	25/8	1020	17/3	7.8	9.4
19 Oct	0100	44.3	87.1	7	18/14	98	00/0	1020	18/2	6.7	4.4
19 Oct	0200	44.3	87.0	7	19/12	98	01/0	1020	19/2	7.8	5.6
19 Oct	0600	44.4	86.3	9	22/09	97	25/8	1013	19/2	7.8	5.6
19 Oct	1200	44.5	87.3	9	23/05	94	28/4	1000	00/0	6.7	6.1
19 Oct	1400	44.6	86.7	9	23/10	96	02/1	1015	23/2	8.9	6.1
19 Oct	1800	44.4	86.4	8	35/17	98	01/8	1015	35/2	8.9	6.1
19 Oct	1900	44.3	86.5	6	36/17	99	01/2	1015	35/2	8.9	8.3
20 Oct	0200	44.5	86.7	2	20/24	99	02/0	1024	20/3	10.0	7.2
21 Oct	1400	44.4	87.0	1	20/26	99	02/0	1015	20/3	7.2	3.9

TABLE 3 continued.

Ship: CITY OF MADISON

Date	Time	Lat.	Long.	Clouds	Wind	Vis	Wx	Pressure	Waves	Air Temp.	Water Temp.
18 Oct	0300	43.1	87.3	0	17/21	99	00/0	1018	17/2	12	12.2
18 Oct	0500	43.1	86.9	0	17/21	99	00/0	1019	17/2	11	11.7
18 Oct	0600	43.2	86.5	1	16/17	99	03/0	1019	17/1	11	12.8
18 Oct	1200	43.2	86.5	8	18/20	98	03/0	1016	18/1	10	13.3
18 Oct	1300	43.1	86.6	9	19/21	98	03/0	1016	19/2	11	13.3
18 Oct	1300	43.1	86.6	9	02/10	97	21/2	1016	02/1	11	13.3
18 Oct	1500	43.0	87.2	9	25/14	97	62/8	1016	18/1	11	11.7
18 Oct	1600	43.0	87.6	9	21/08	97	60/8	1017	18/1	10	11.7
18 Oct	2100	43.1	87.6	1	19/08	98	01/1	1015	18/0	11	12.2
18 Oct	2300	43.0	87.5	8	18/12	98	21/6	1013	18/1	10	11.7
19 Oct	0100	43.2	87.3	8	18/11	98	03/2	1013	18/1	10	11.1
19 Oct	1300	43.2	87.5	8	29/05	97	21/6	1012	29/0	09	11.1
19 Oct	1400	43.2	87.6	8	22/07	97	50/5	1012	22/0	09	11.1
19 Oct	1500	43.1	87.5	8	23/06	98	16/5	1014	23/0	10	12.2
19 Oct	1600	43.1	87.7	7	34/13	98	01/2	1010	34/0	14	11.7
19 Oct	2100	43.2	87.7	1	36/11	99	01/1	1015	36/0	09	11.7
19 Oct	2200	43.2	87.3	1	33/11	99	02/0	1015	36/1	13	11.7
19 Oct	2300	43.2	87.2	1	36/17	99	01/1	1015	36/1	13	11.1
19 Oct	2400	43.2	87.0	2	32/13	99	02/1	1015	32/1	11	11.1

TABLE 3 continued.

Ship: S.S. SPARTAN

Date	Time	Lat.	Long.	Clouds	Wind	Vis	Wx	Pressure	Waves	Air Temp.	Water Temp.
18 Oct	0500	43.0	87.5	0	17/09	98	00/0	1014	17/0	8.9	11.7
18 Oct	0600	43.1	87.3	0	19/15	98	00/0	1014	17/0	10.6	10.6
18 Oct	0700	43.3	87.1	0	18/20	98	00/0	1013	18/2	11.1	13.9
18 Oct	0800	43.4	87.0	0	16/20	98	00/0	1012	17/2	10.6	12.2
18 Oct	0900	43.5	86.4	0	15/23	98	00/0	1013	17/2	9.4	12.2
18 Oct	1000	43.4	86.4	0	16/24	98	00/0	1013	17/2	8.9	13.3
18 Oct	1200	44.0	86.3	2	16/17	98	03/1	1013	17/2	5.6	13.3
18 Oct	1300	44.0	86.4	9	17/18	98	02/2	1013	17/2	7.8	12.2
18 Oct	1400	44.0	87.1	9	15/24	98	02/2	1011	16/2	7.8	6.7
18 Oct	1500	44.1	87.3	9	16/15	97	02/2	1011	16/2	6.1	6.7
18 Oct	1700	44.1	87.3	8	18/22	97	20/5	1009	16/3	6.7	6.7
18 Oct	1800	44.0	87.1	8	17/16	98	03/5	1010	16/3	8.9	6.1
18 Oct	1900	44.0	86.7	7	13/10	98	01/2	1010	16/3	7.8	12.2
18 Oct	2000	44.0	86.3	7	13/10	98	01/2	1010	16/3	7.8	12.8
19 Oct	0100	44.0	86.4	9	16/16	98	02/2	1009	16/2	7.8	12.2
19 Oct	0200	44.0	87.1	9	17/15	98	02/2	1009	16/2	7.8	7.8
19 Oct	0300	44.0	87.3	9	19/13	98	50/5	1008	17/2	6.7	6.7

The entries in Table 3 are coded by the standard Weather Bureau code for ship observations: Time is given as GMT; lat. and long. to the nearest tenth degree; cloud cover is in eighths, with code 9 indicating obscurred sky; wind is given as dd/ss, where dd is the direction in 10-degree units, and ss is the wind speed in knots; visibility is the standard code; weather is given as ww/W where ww is coded as present weather, and W is past weather during the observation period; pressure is given in millibars; waves are coded as dd/h, where dd is the direction from in 10-degree units, and h is coded height; and air and water temperature are in degrees Celsius.

Figures 16 through 20 show the development of the wind field on 20 October and 21 October. By the time of the wave flight that was carried out on 21 October, the wind had been blowing from the south at speeds of 25-35 kts for 24 hours.

WAVE RUN 21 OCTOBER 1966

The flight path for the wave run made on 21 October 1966 is shown in Figure 21. The flight began at the north end of the lake at 1750 GMT (1250 EST), with the course being altered at 1801, 1814, and 1819:30 GMT so that the wave measurements would be made normal to the direction of the approaching wave fronts. The flight was made "upwind," but with the actual direction defined by the local wave structure. The flight was broken off at 1819:30 and resumed at 1831 GMT so that the measurements could be made under better conditions of clear fetch. The flight was broken off again at 1841 to replenish the paper supply in the analog wave recorder, and resumed again at 1849 GMT. The flight continued until 1915 GMT.

The wave run was carried out under nearly ideal conditions. The weather during the early part of the week was generally light. The wave run took place after 24 hours of constant (25-35 kts) south winds. The resulting conditions were ideal for the documentation of the build-up of a wave train with increasing fetch under the effects of a strong offshore wind.

The analog wave records were digitized by the U.S. Naval Oceanographic Office, and gravity wave power spectra were computed for consecutive, but independent portions of 2-minutes duration over the full length of the continuous record. At the aircraft ground speed of about 165 knots (275 ft/sec), the 2-minute wave profile corresponds to a distance of about 5.5 nautical miles. This interval may be too great for portions of the record near the

coast where changes are occuring more rapidly than is the case 50 to 100 miles down wind. For subsequent analysis, the segments of these independent 2-minute records (say the first and fifth mile) should be analyzed to make certain that the statistical properties show that the 2-minute (or lesser) portion of record is homogeneous.

Figure 22 shows the wave height power spectra for successive 2-minute periods (5.5 mile distances) starting from a point 9 nautical miles off the windward shore through a fetch of 164.6 nautical miles. The computed spectra were corrected for instrument response, and transformed to account for the speed of the moving platform. The upper and lower 90% confidence limits can be determined from the spectral curves given in the above figure by multiplying by 1.300 (the upper confidence limit factor) or by 0.730 (the lower confidence limit factor).

PHOTOGRAPHIC RESULTS

The CA-8 mapping camera was used to provide mapping coverage of three shore-line areas that are now sites of specific Great Lakes Research Division research programs. Further aerial mapping was carried out in the north end of the lake to provide documentary information for use in the development of a program for the remote detection of "doubtful reefs." The photographic mapping was with Ektachrome film.

Supplemental photography was carried out with four hand-held cameras to test the applicability of various film types to Great Lakes research programs. These cameras were loaded with High-speed Ektachrome, aero-infrared Ektachrome, and Plus X panchromatic film. The black-and-white film was used in combination with a Wratten No. 25 filter.

Selected examples of the hand-held photography are shown in figures 23 and 24.

Figure 23a shows the harbor plume at Manistee, Michigan. The line of demarcation between lake water mass and the harbor effulent is enhanced by apparent nearshore sediment transport around the south pier. Figure 23b is a typical example of a small stream delta on the Michigan shore. Periphyton concentrations occurring in this habitat appear red or reddish brown on infrared Ektachrome. Figure 23c bedrock control of shoreline structures in the Little Traverse Bay region. Figure 23d shows periphyton concentrations occurring on shoals around Isle aux Galets in Northern Lake Michigan. Figure 23e shows the turbidity patterns around North Point. Figure 23f is a second example of a small stream mouth along the Lake Michigan beaches. Color reproductions of figures 23a and 23b are included at the back of this report.

Figure 24a shows the effect of sun angle upon photography of wave refraction patterns. Figure 24b is an example of a wave refraction pattern caused by a submerged reef. Figure 24c shows a sediment load carried along shore and entrained in an off-shore current component on the north side of Cat-Head Point in upper Lake Michigan. Figure 24d shows the double sand bar structure characteristic of the Michigan shore line of Lake Michigan. Figure 24e shows the development of a sediment plume along the shore line. Figure 24f shows the harbor plume at Port Washington, Wisconsin. The visual contrast of all of these features is enhanced by the use of infrared Ektachrome.

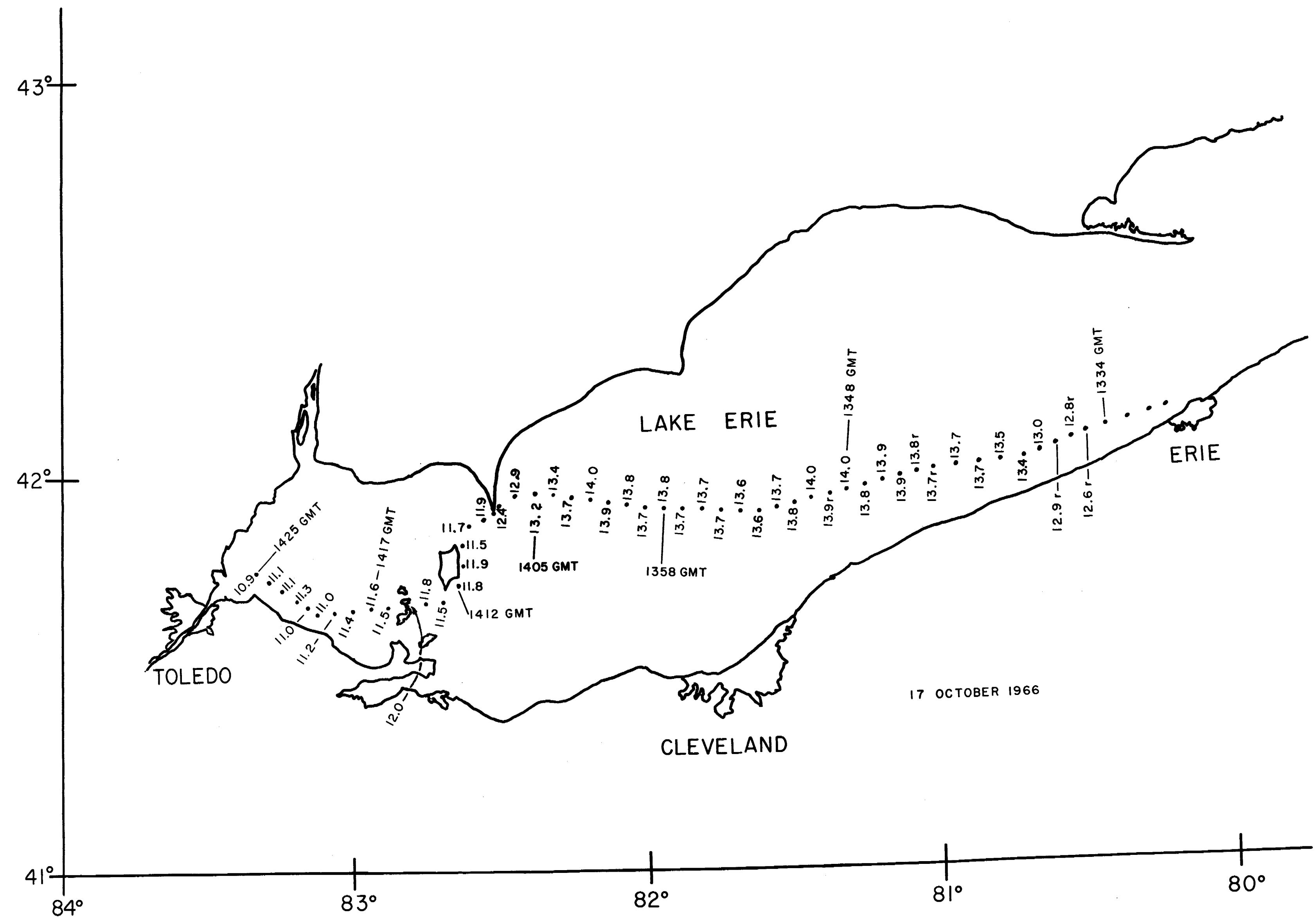


FIG. 1. Lake Erie flight path, 17 October 1966, showing one-minute average ART temperatures.

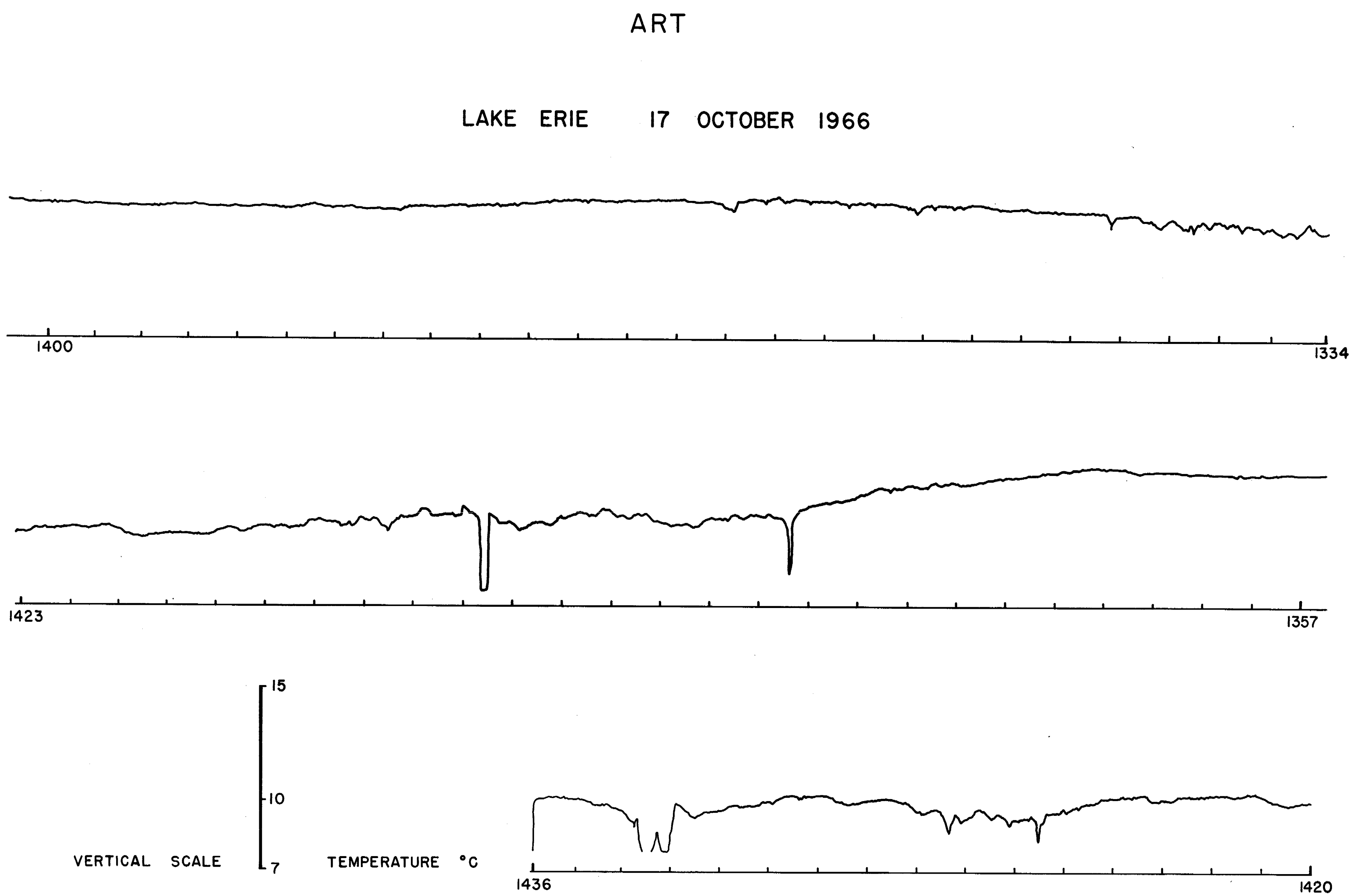


FIG. 2. Tracing of ART (Airborne Radiation Thermometer) record from Lake Erie flight, 17 October 1966.

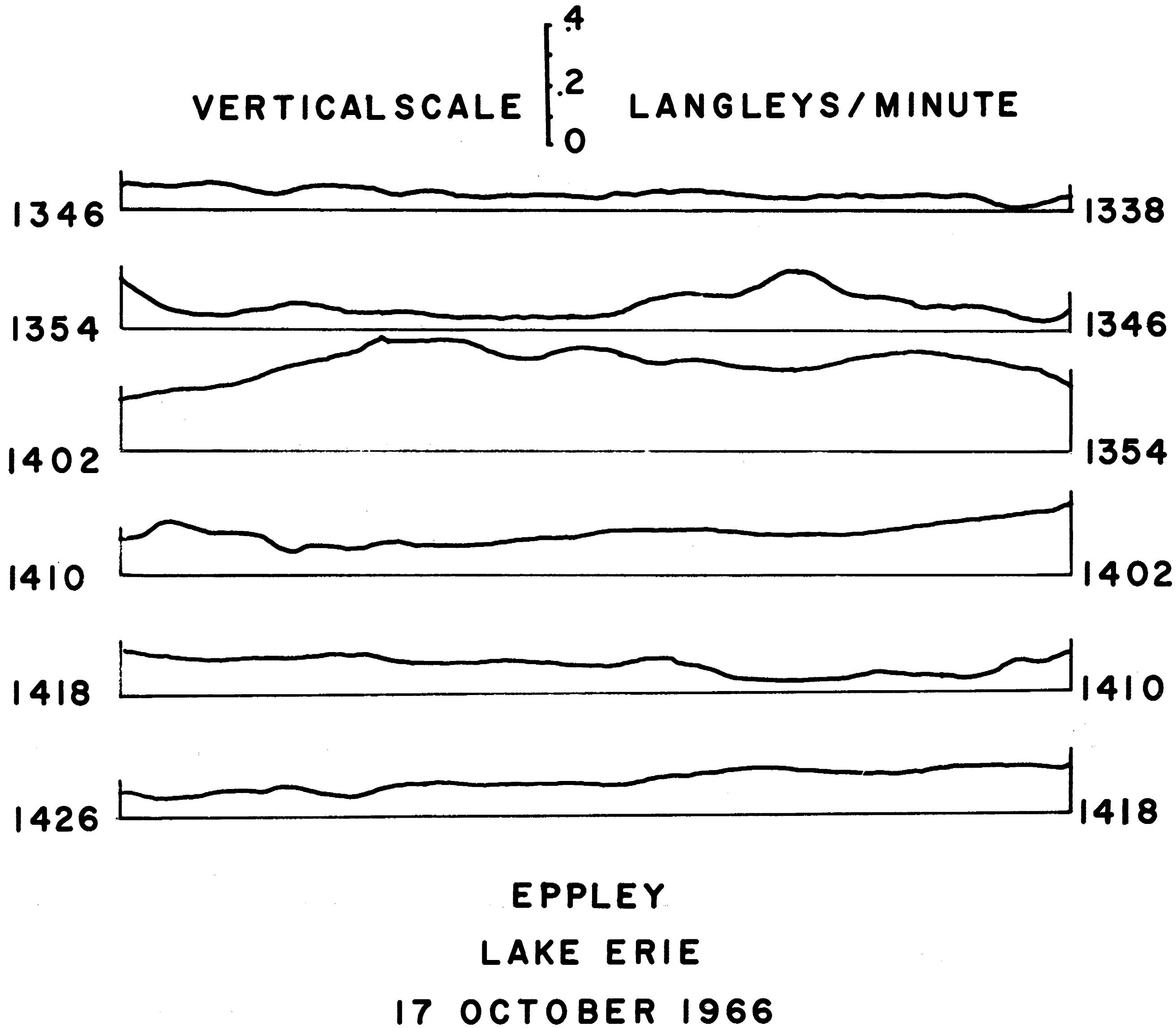


FIG. 3. Incoming solar radiation.

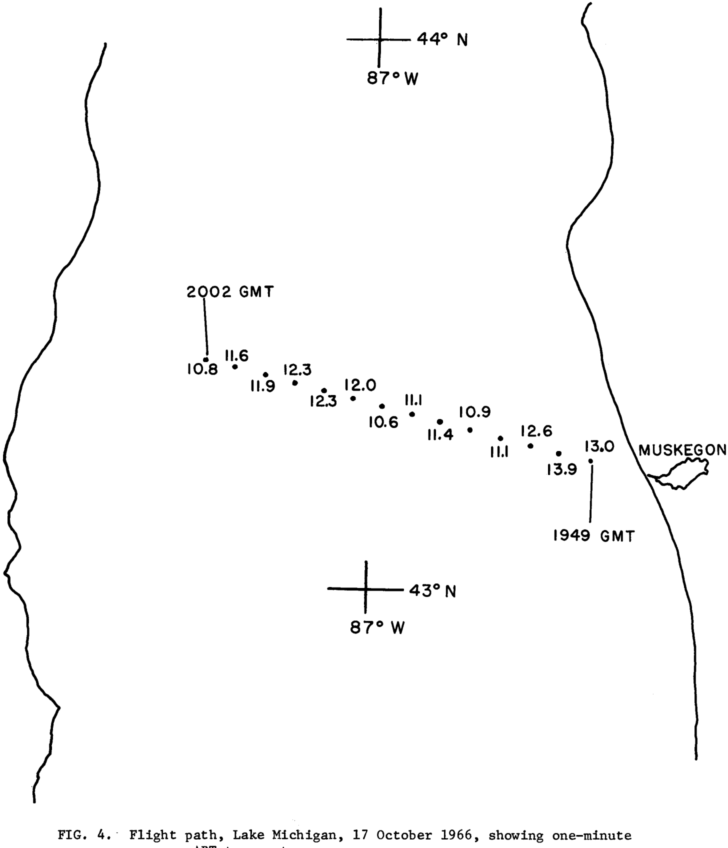


FIG. 4. Flight path, Lake Michigan, 17 October 1966, showing one-minute average ART temperatures.

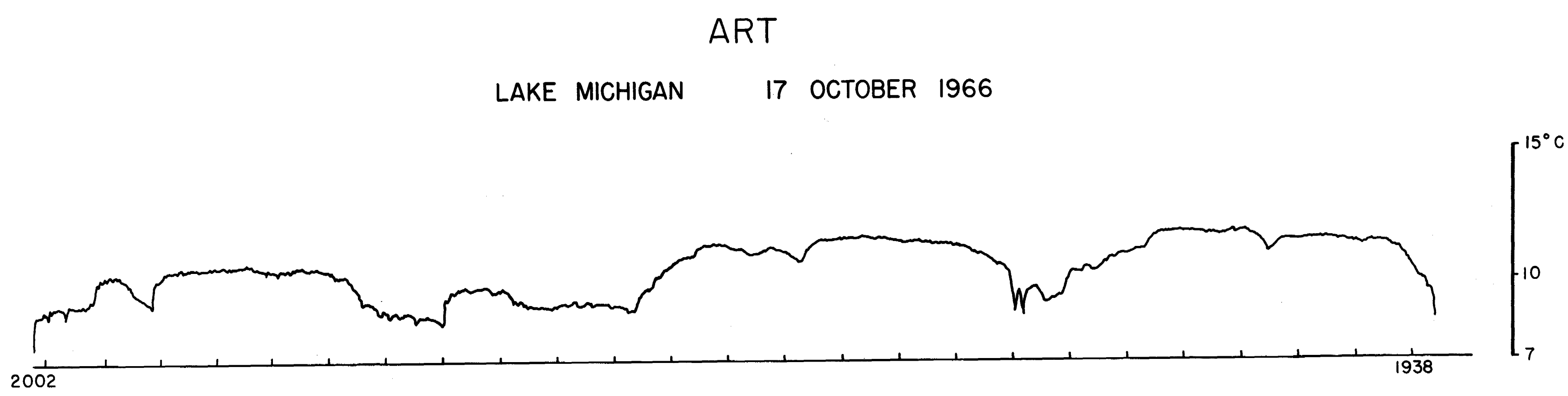


FIG. 5. Tracing of ART record, Lake Michigan, 17 October 1966.

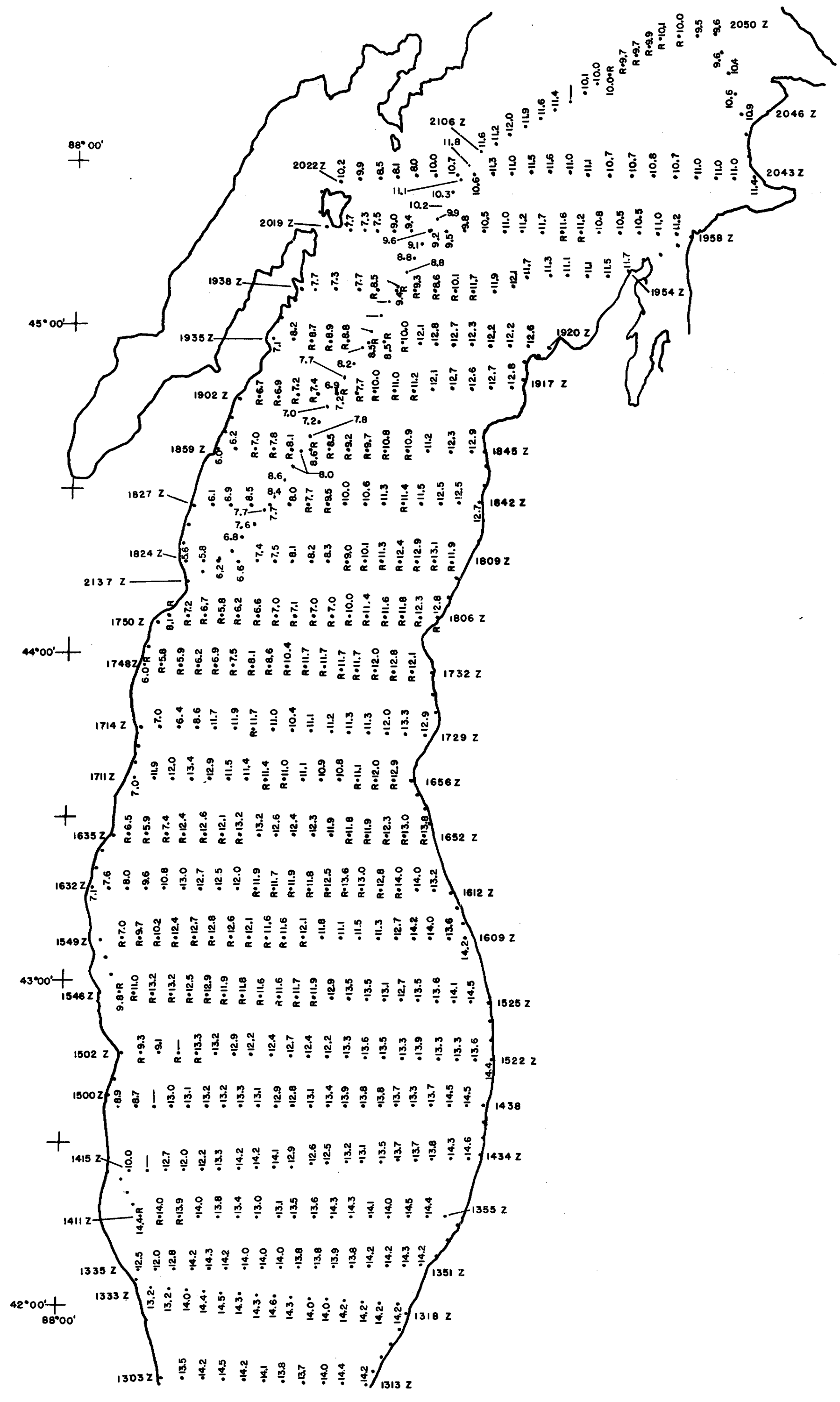


FIG. 6. Flight path, Lake Michigan, 18 October 1966, showing one-minute average ART temperatures.

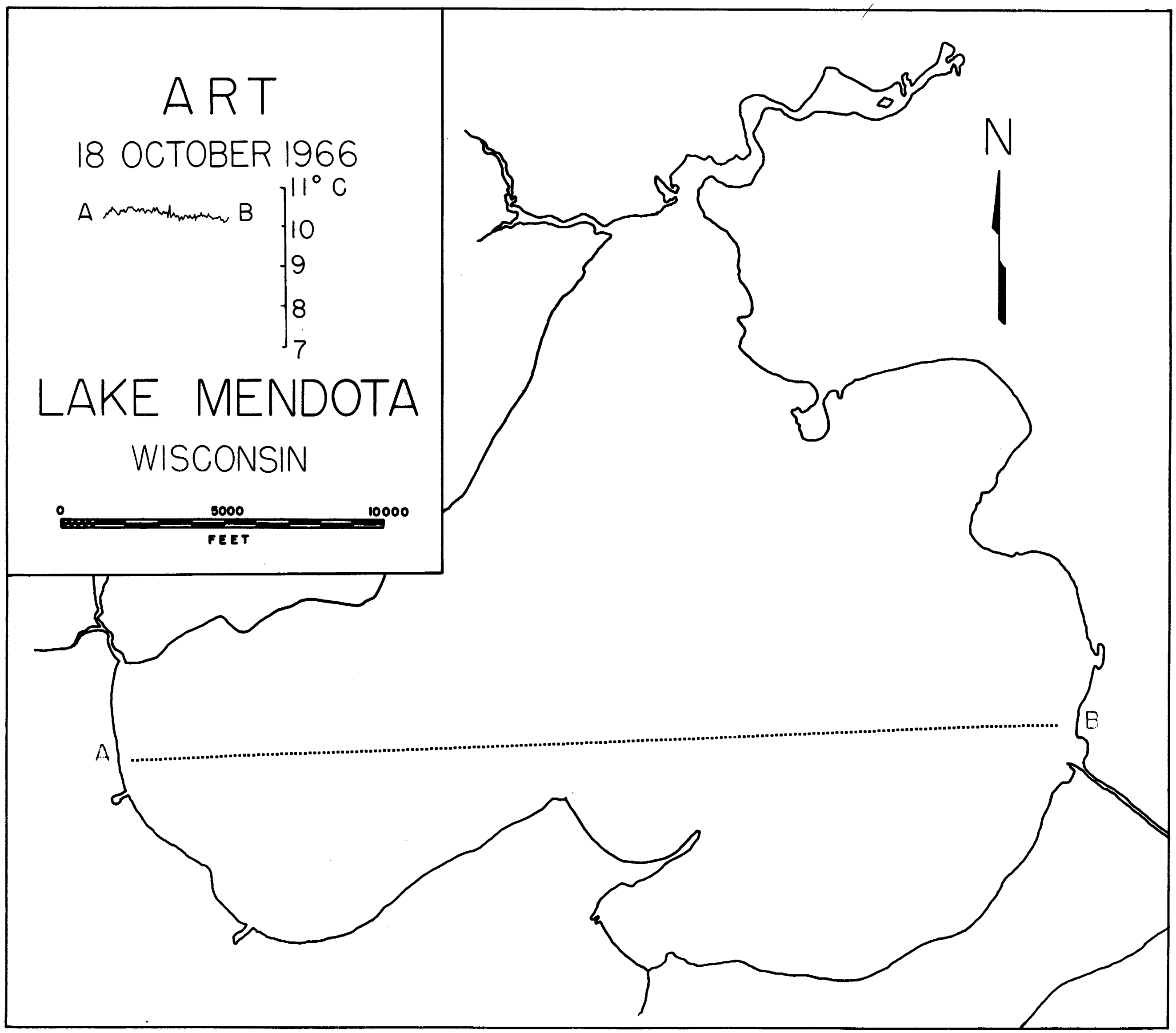


FIG. 7. Flight path and tracing of ART record, Lake Mendota, 18 October 1966.

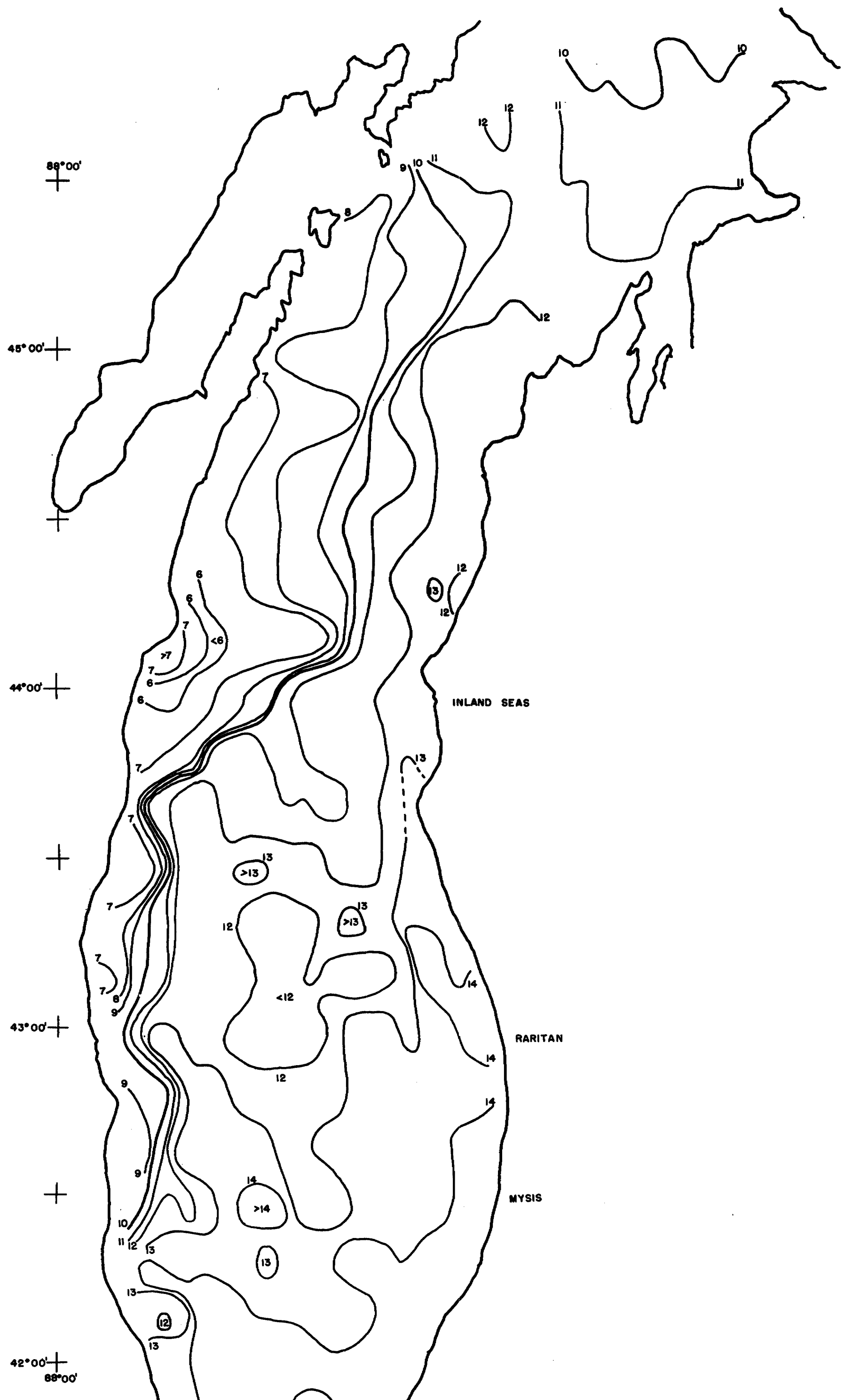


FIG. 8. Isotherms plotted from one-minute average ART temperatures. Lake Michigan, 18 October 1966.

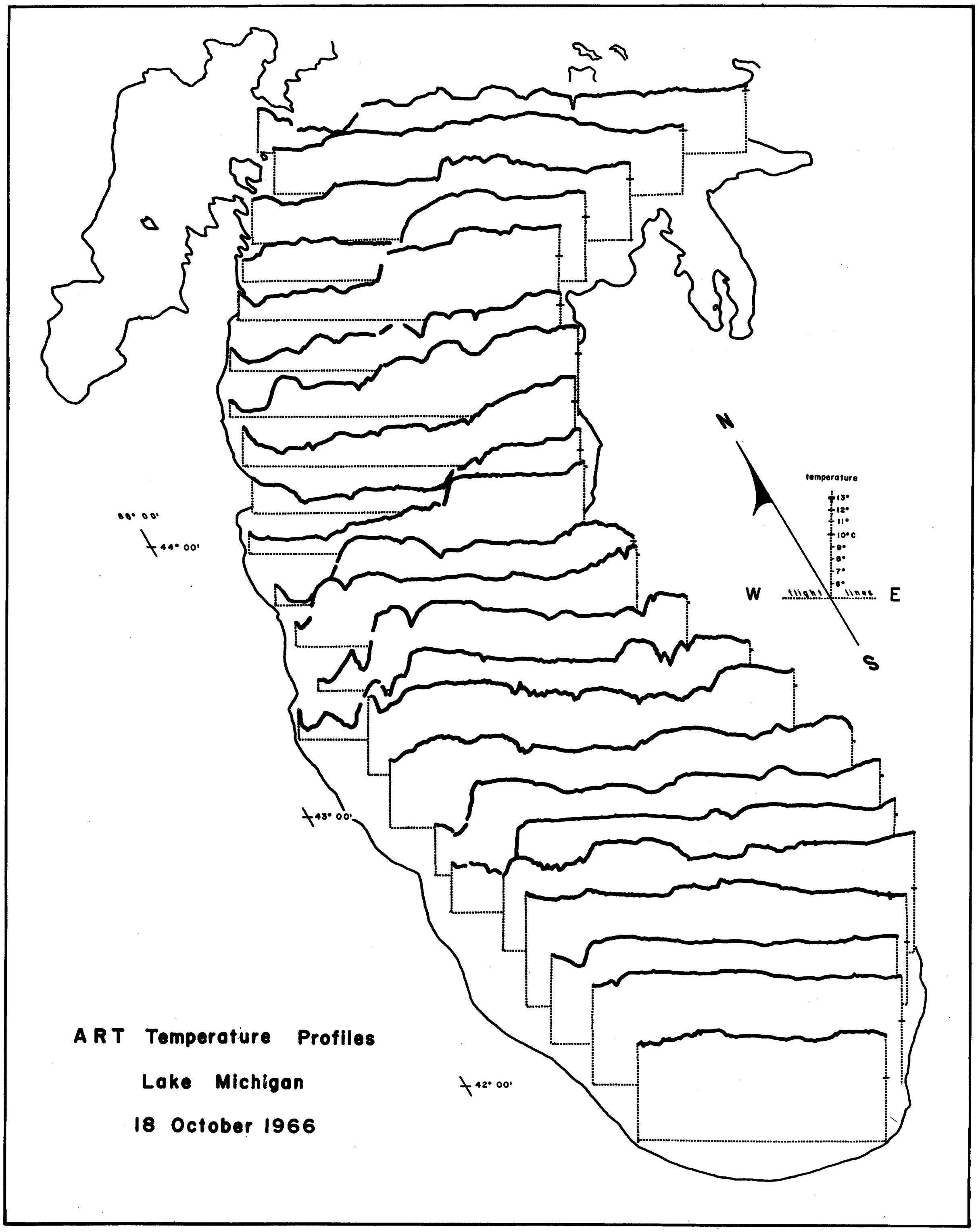


FIG. 9. Isometric projection of tracings of ART record. Lake Michigan, 18 October 1966.

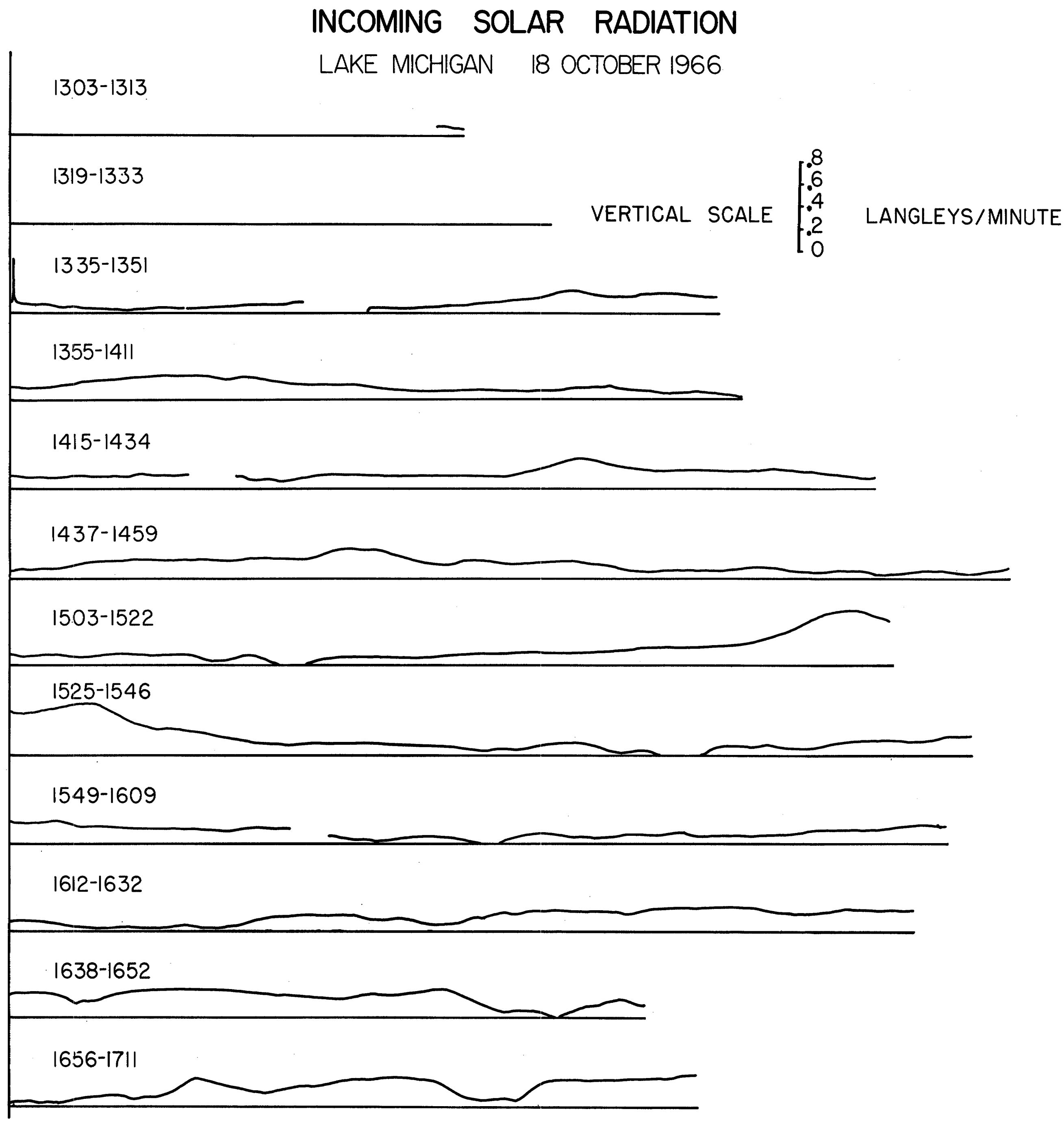
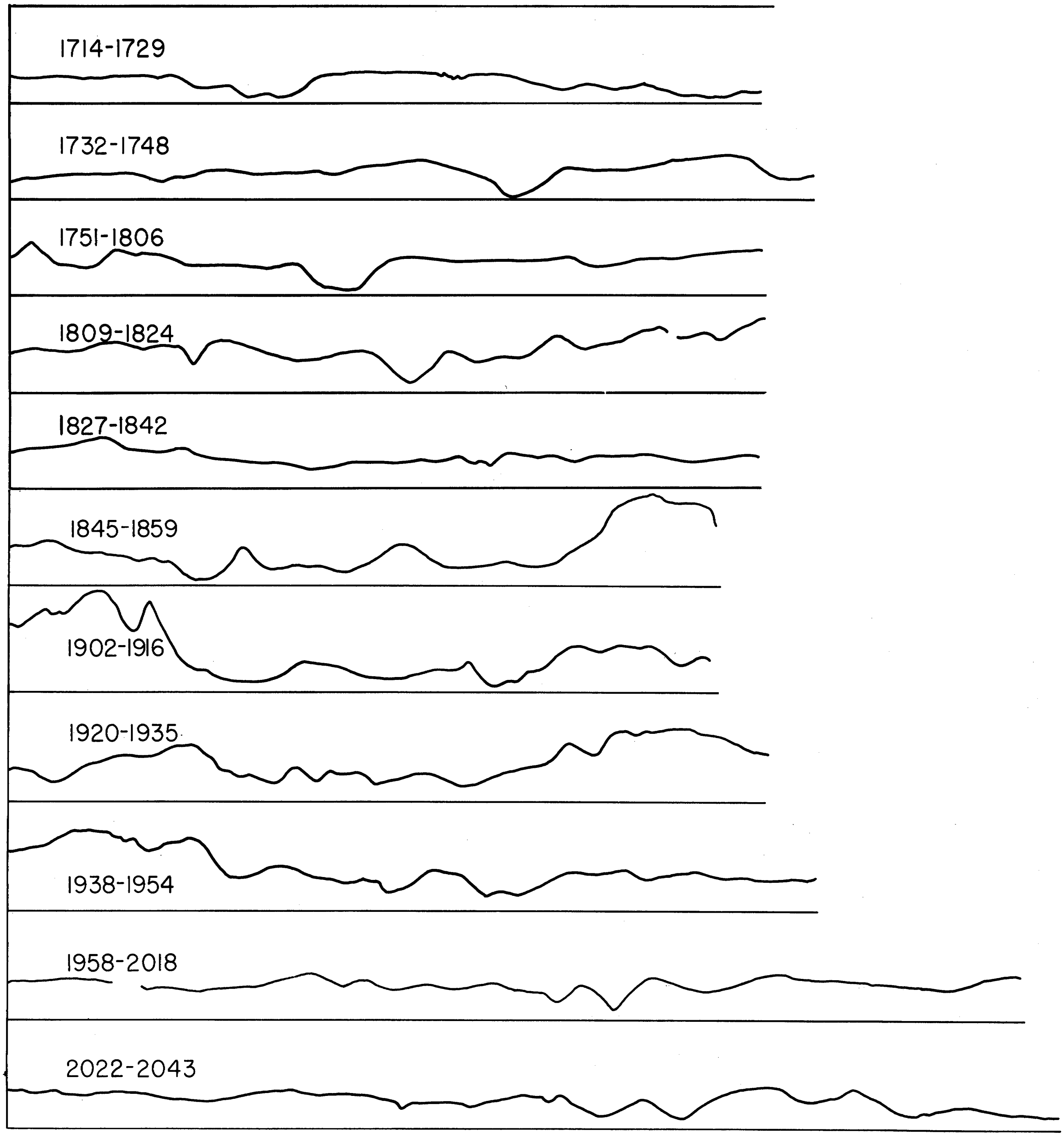


FIG. 10. Incoming solar radiation, Lake Michigan, 18 October 1966.



1714-1729
1732-1748
1751-1806
1809-1824
1827-1842
1845-1859
1902-1916
1920-1935
1938-1954
1958-2018
2022-2043

FIG. 10 (cont.).

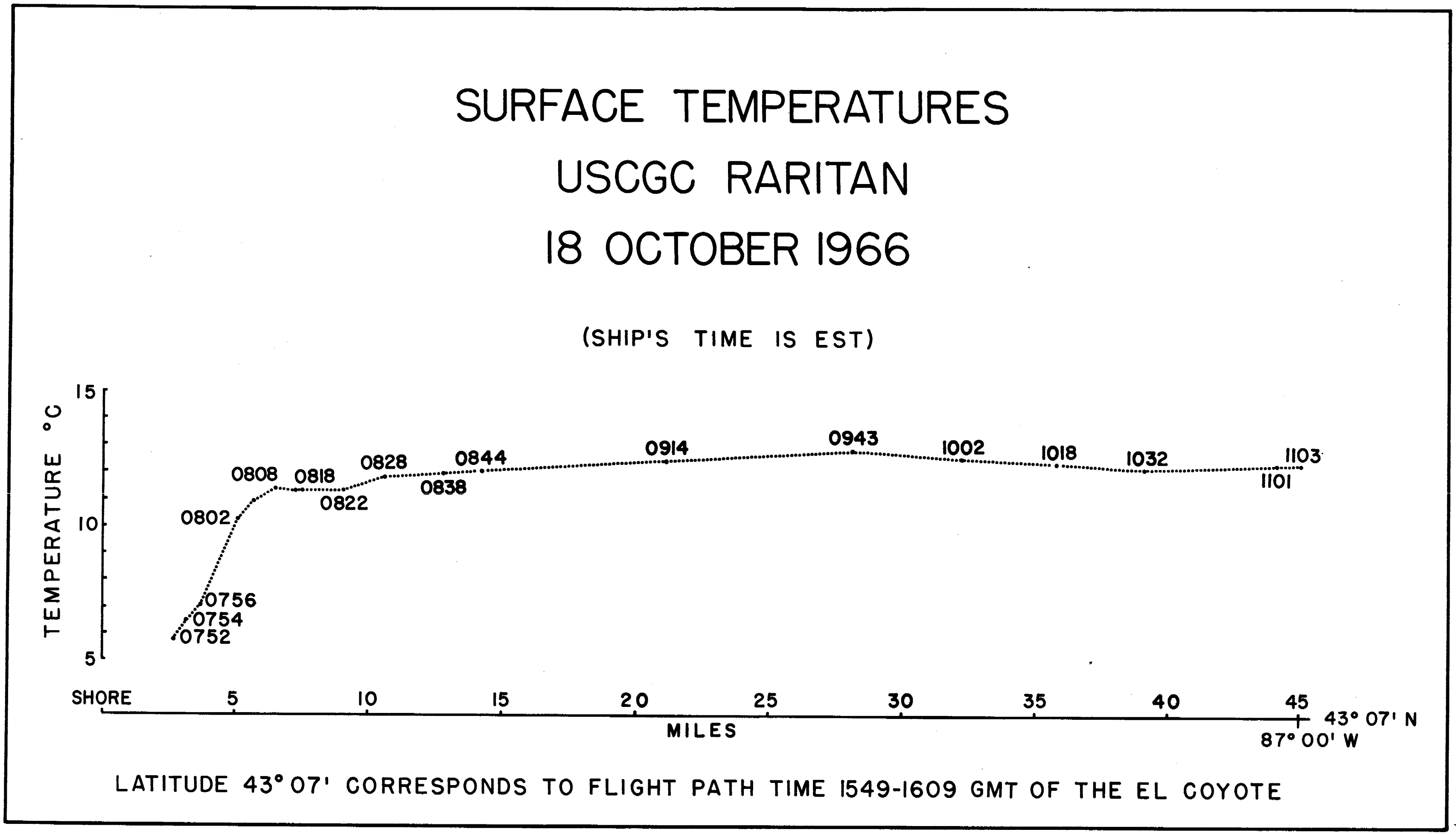


FIG. 11. Lake Michigan surface temperature from USCGC RARITAN.

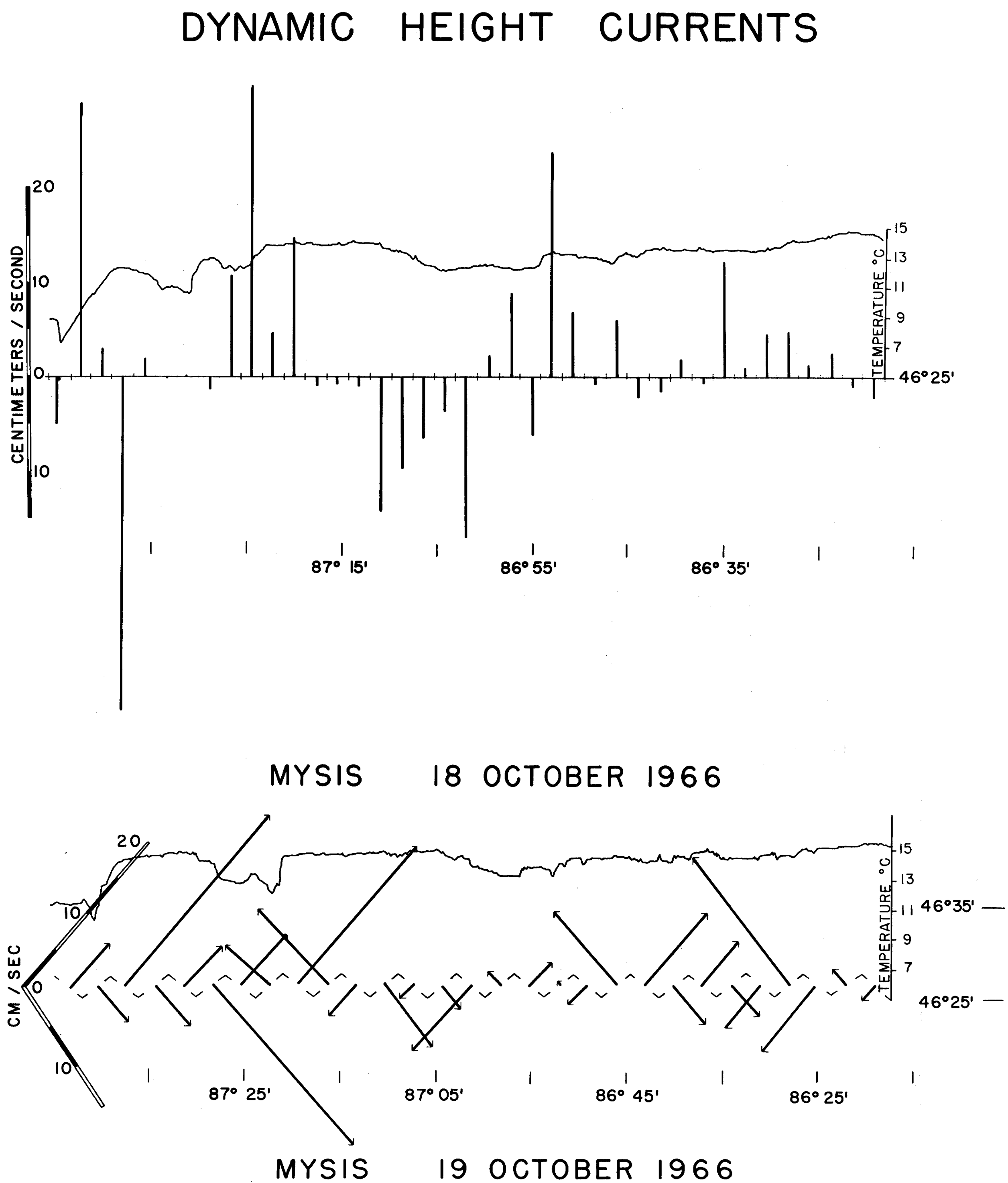


FIG. 12. Dynamic height currents computed for 0-10 meter layer, and surface temperature transects, Lake Michigan, 18 October 1966.

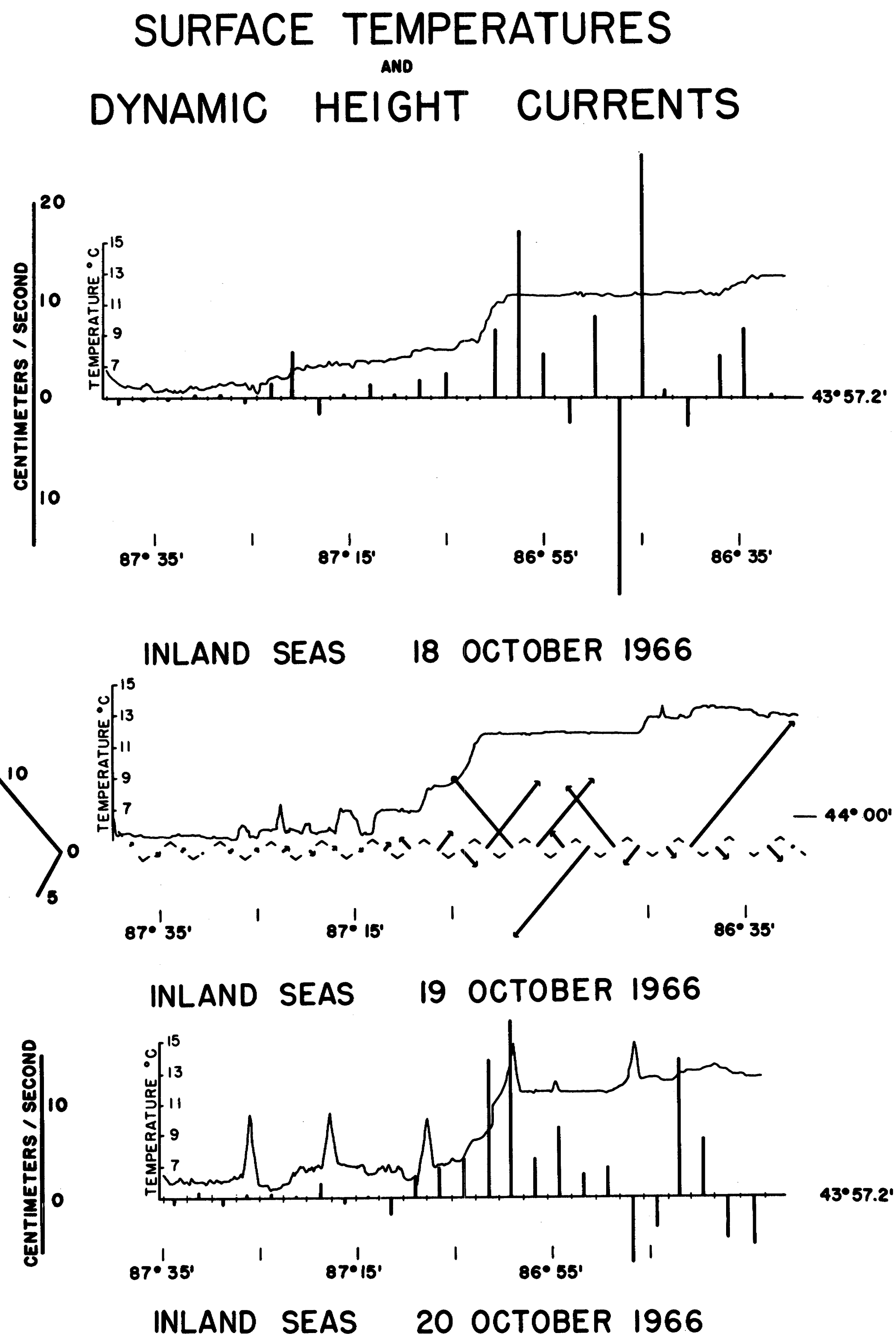


FIG. 13. Dynamic height currents computed for 0-10 meter layer, and surface temperature transects, Lake Michigan, 18 October 1966.

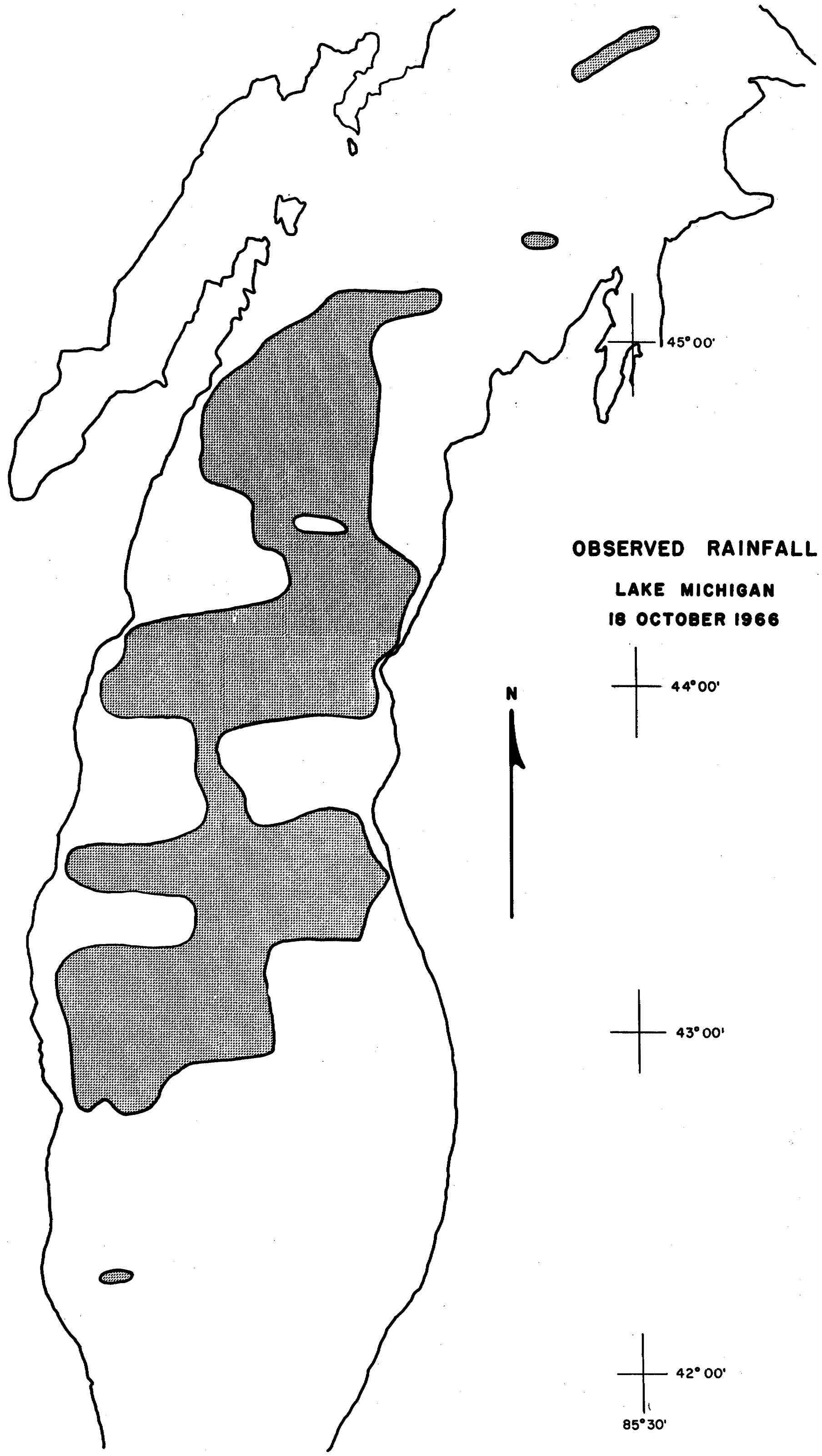


FIG. 14. Rainfall observed along flight path of EL COYOTE, Lake Michigan 1303 Z-2137 Z, Lake Michigan, 18 October 1966.

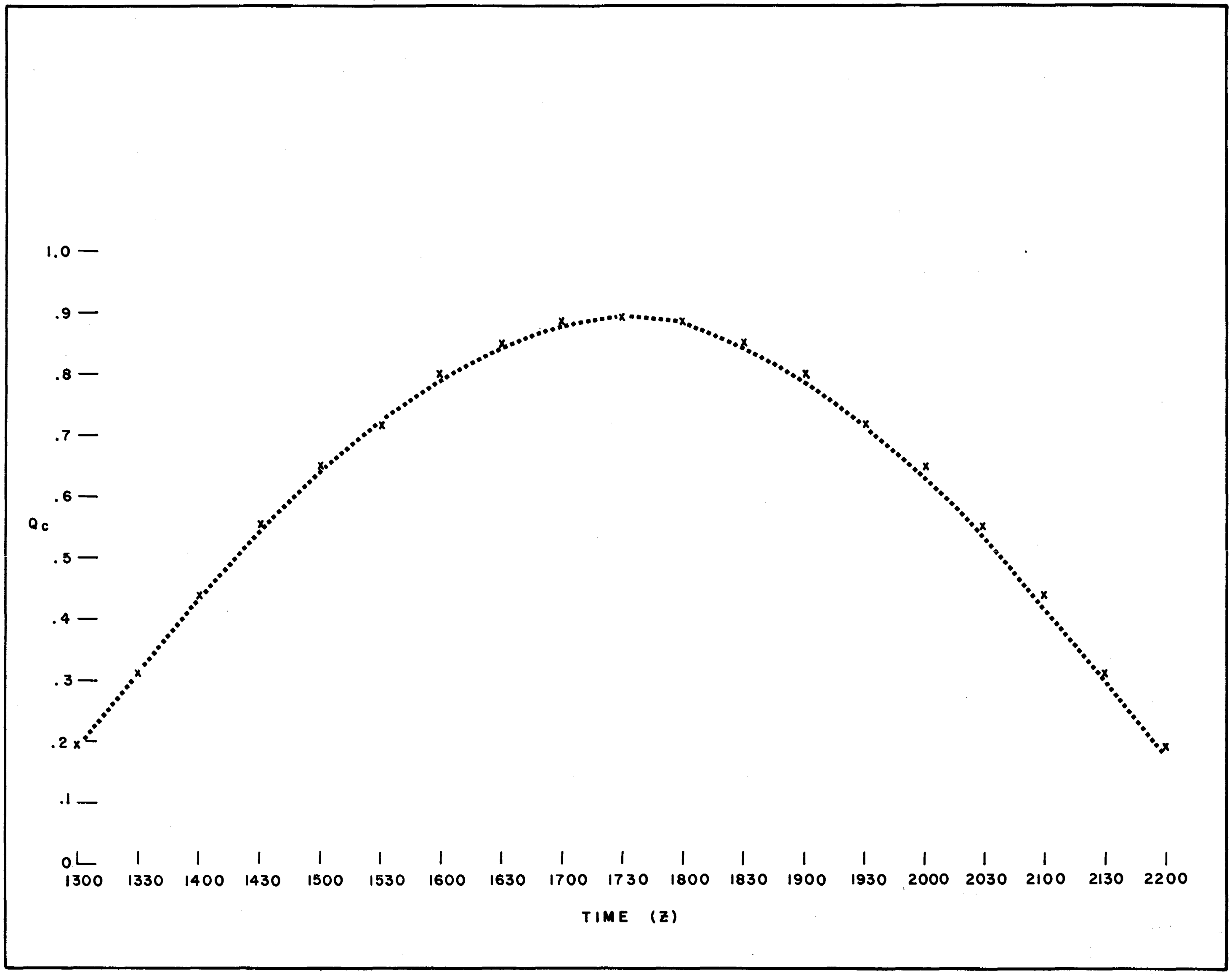


FIG. 15. Normal solar radiation in Ly/min for Lake Michigan, 18 October.

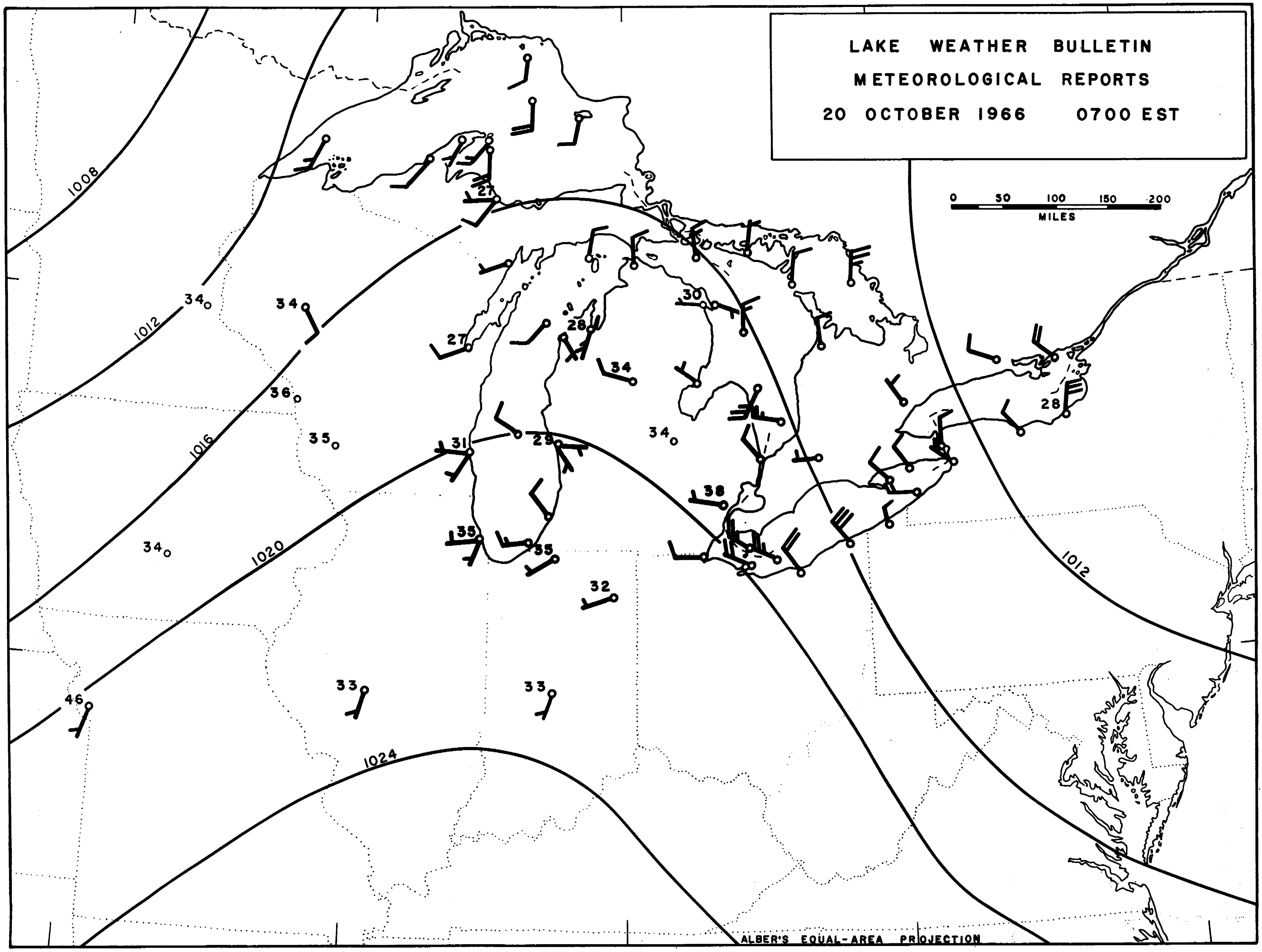


FIG. 16. Wind, pressure, and temperature field 1200 GMT (0700 EST), 20 October 1966.

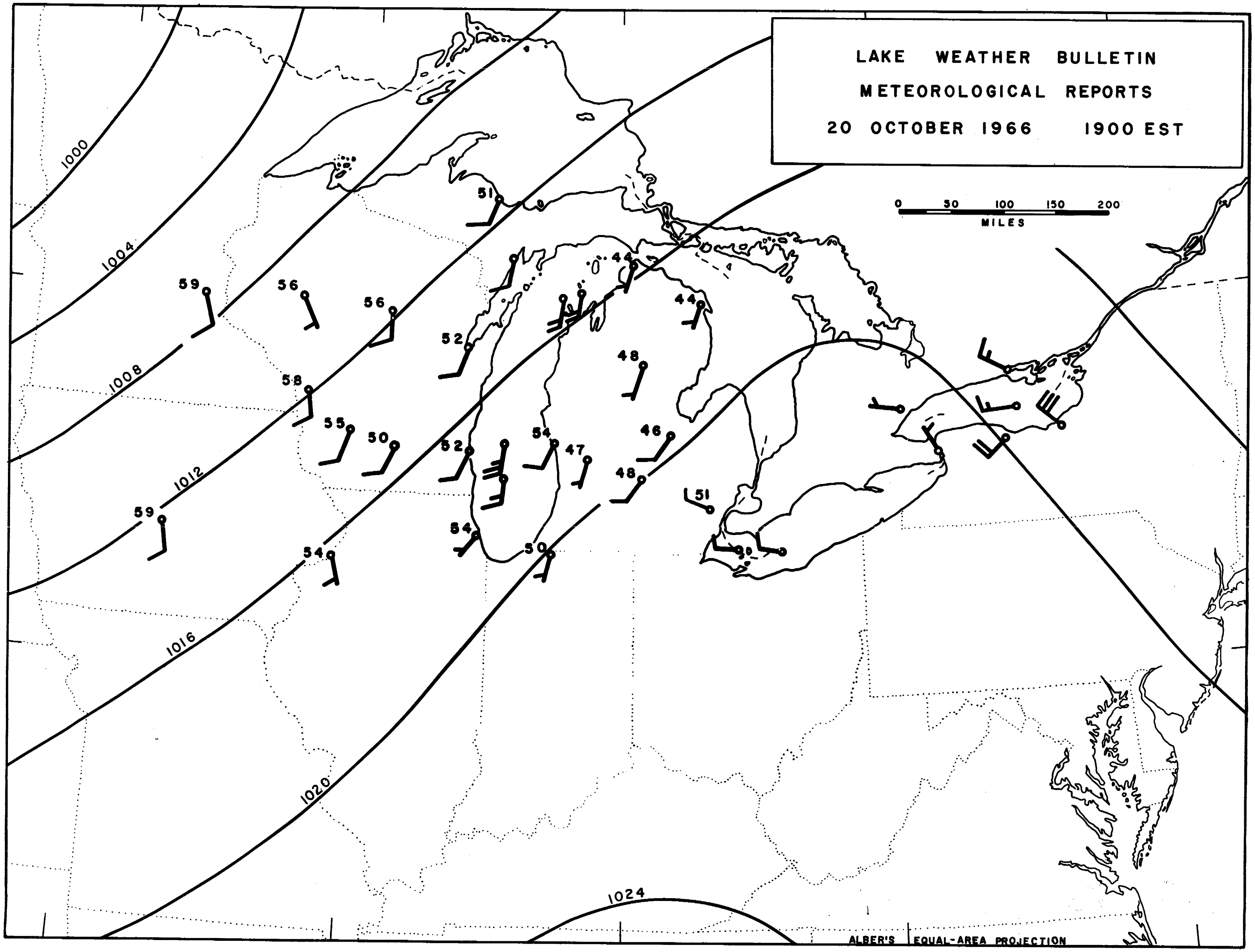


FIG. 17. Wind, pressure, and temperature field 2400 GMT, 20 October 1966.

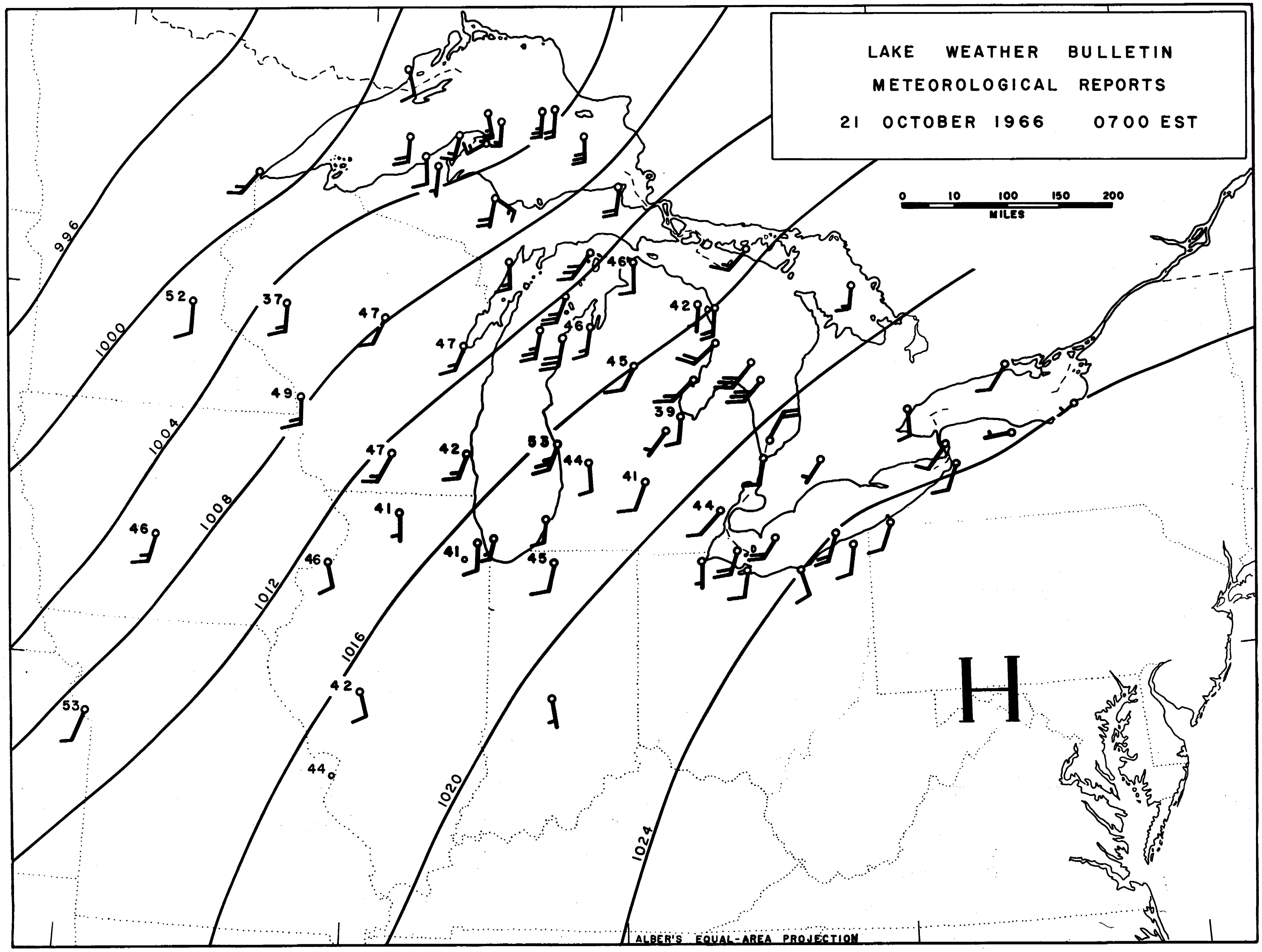


FIG. 18. Wind, pressure, and temperature field 1200 GMT, 21 October 1966.

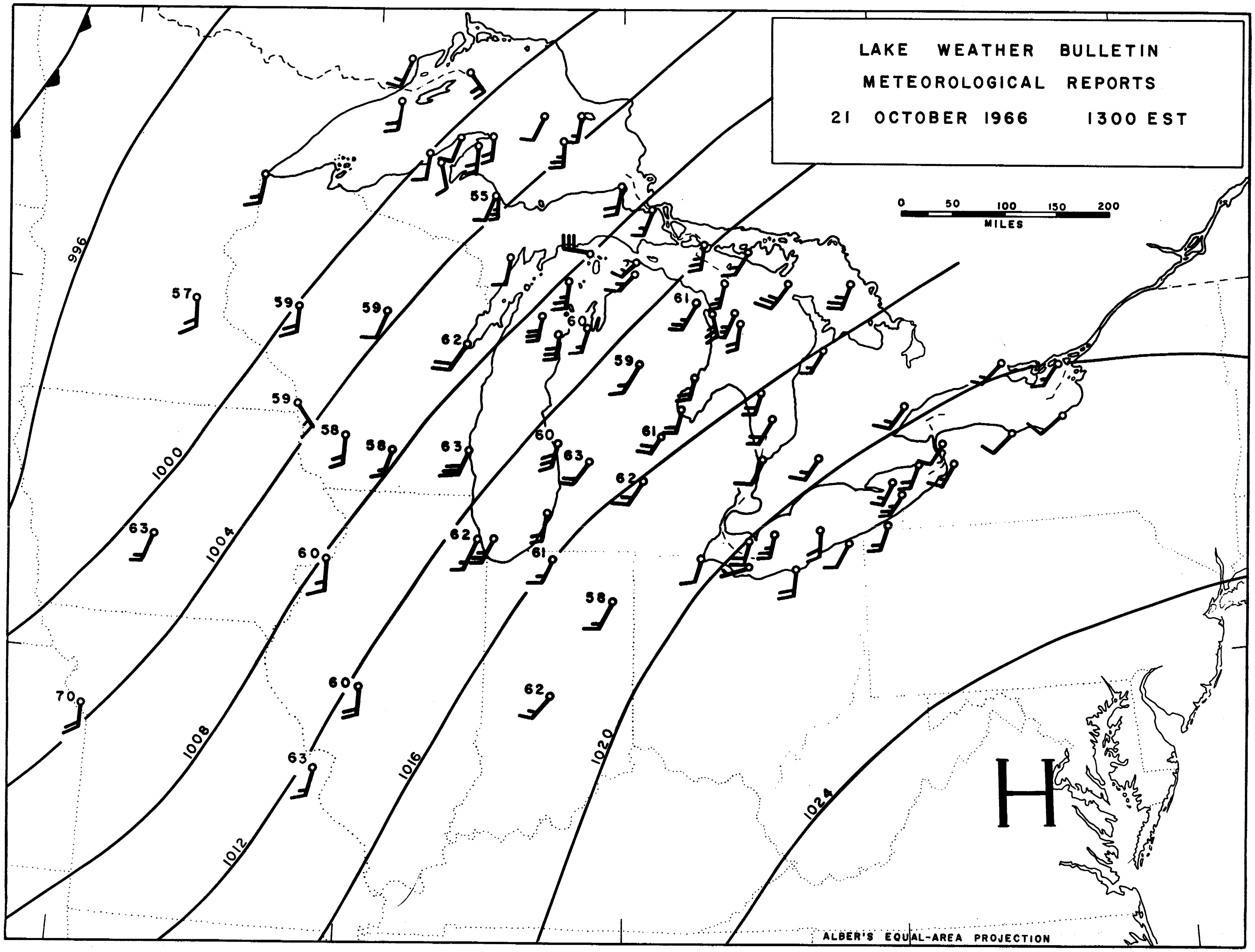


FIG. 19. Wind, pressure, and temperature field 1800 GMT, 21 October 1966.

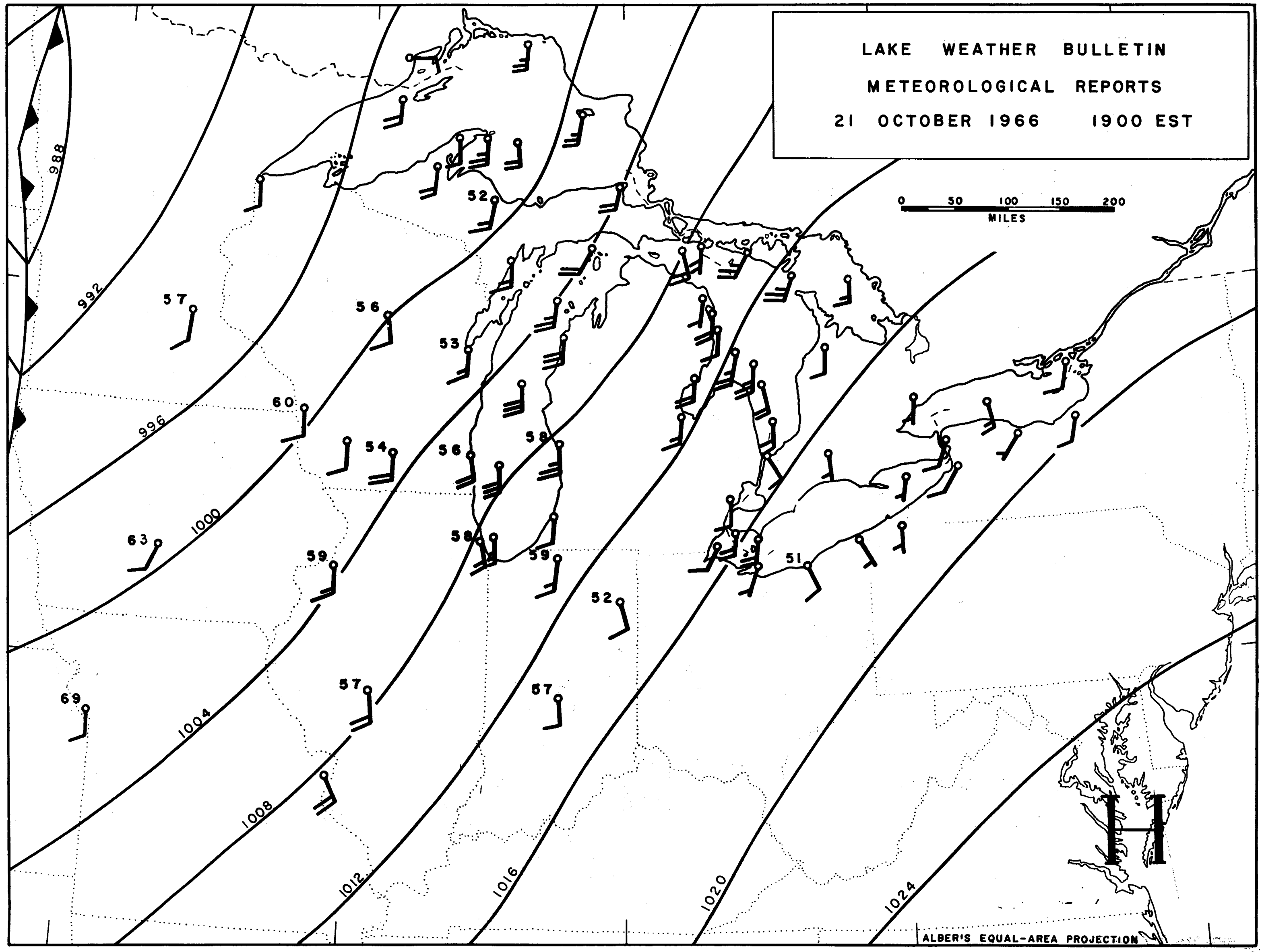


FIG. 20. Wind, pressure, and temperature field 2400 GMT, 21 October 1966.

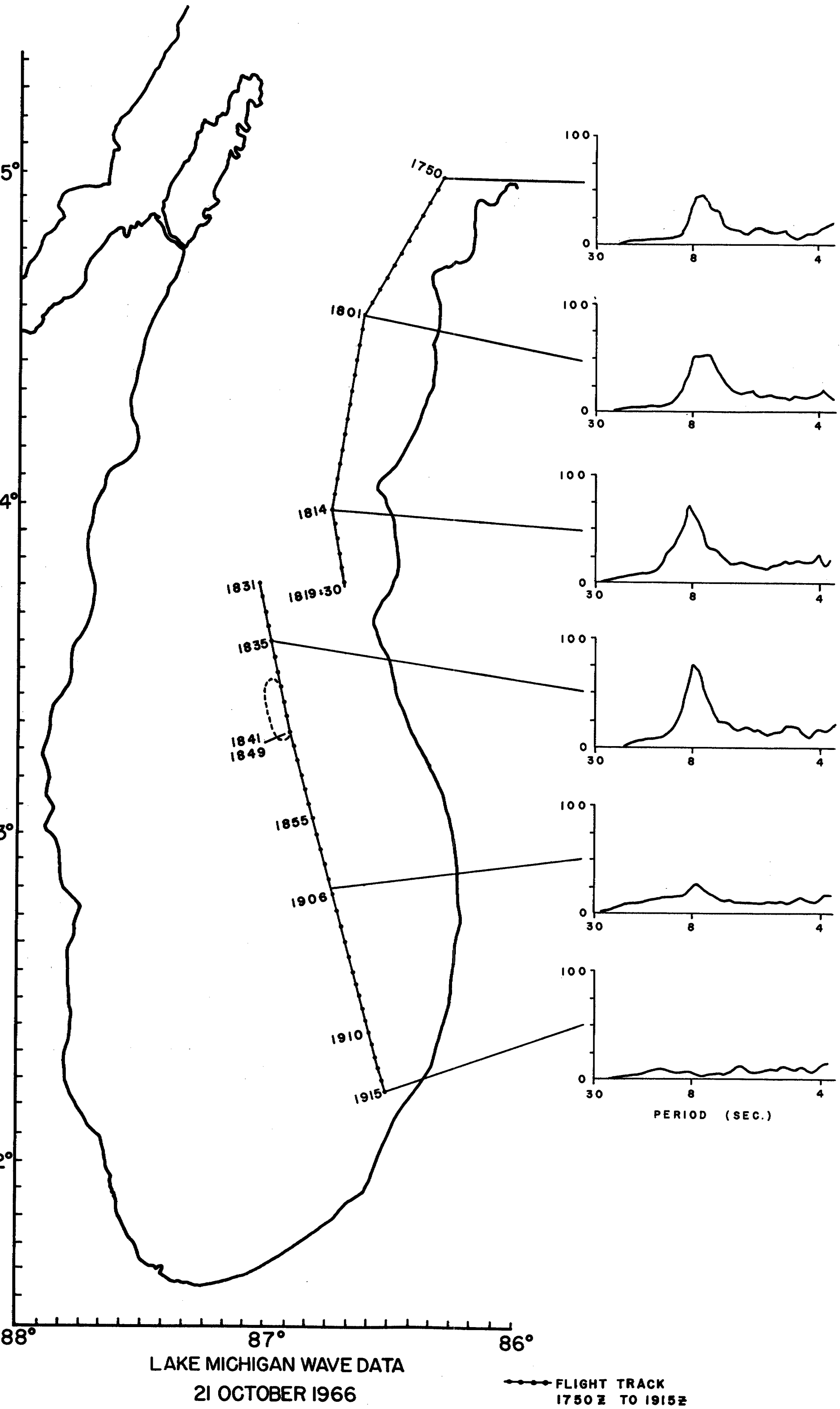


FIG. 21. Flight path and selected wave spectra, wave run, Lake Michigan, 21 October 1966.

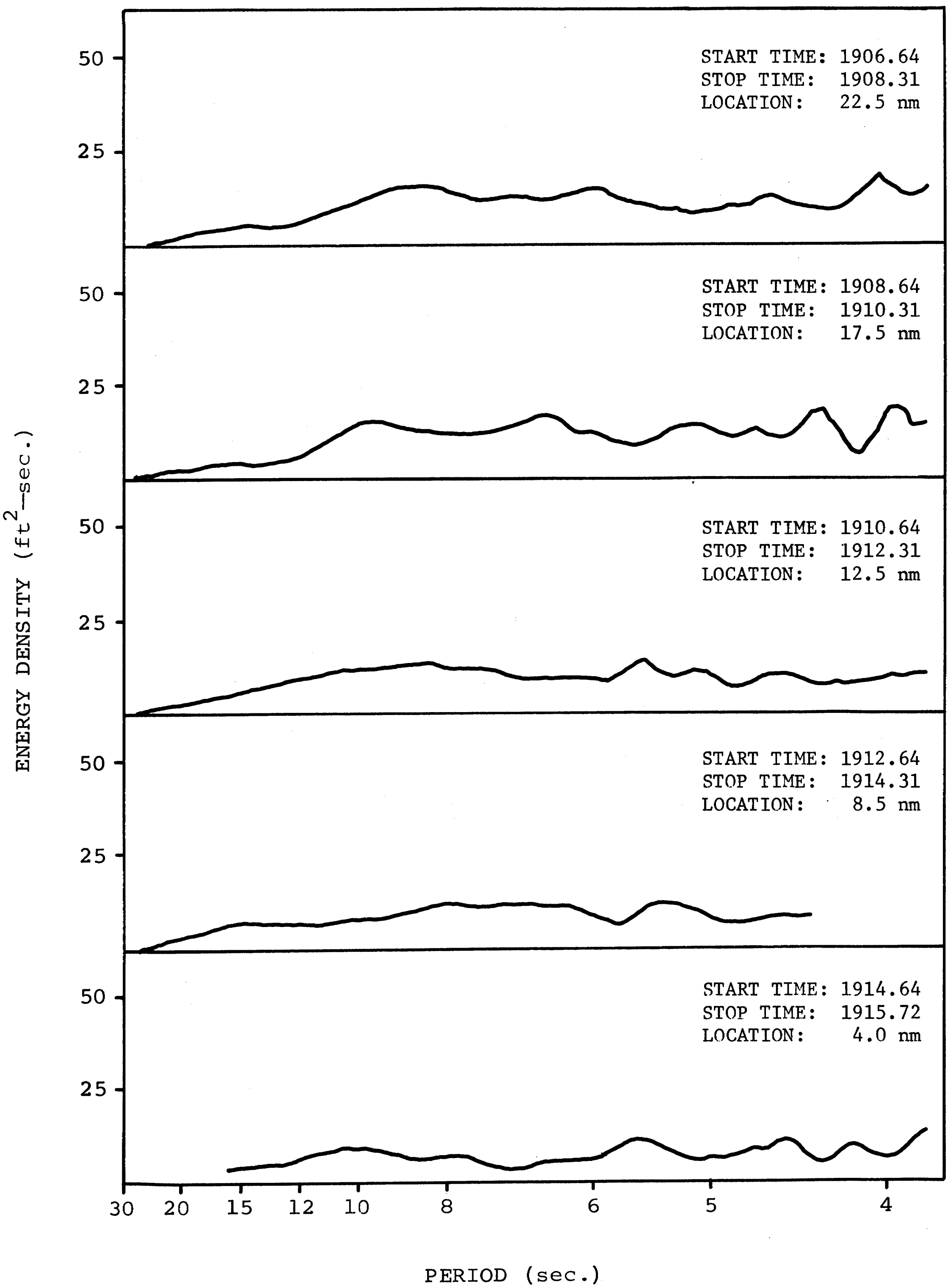


FIG. 22. Wave spectra computed for successive 2-minute periods during Lake Michigan wave run 21 October 1966.

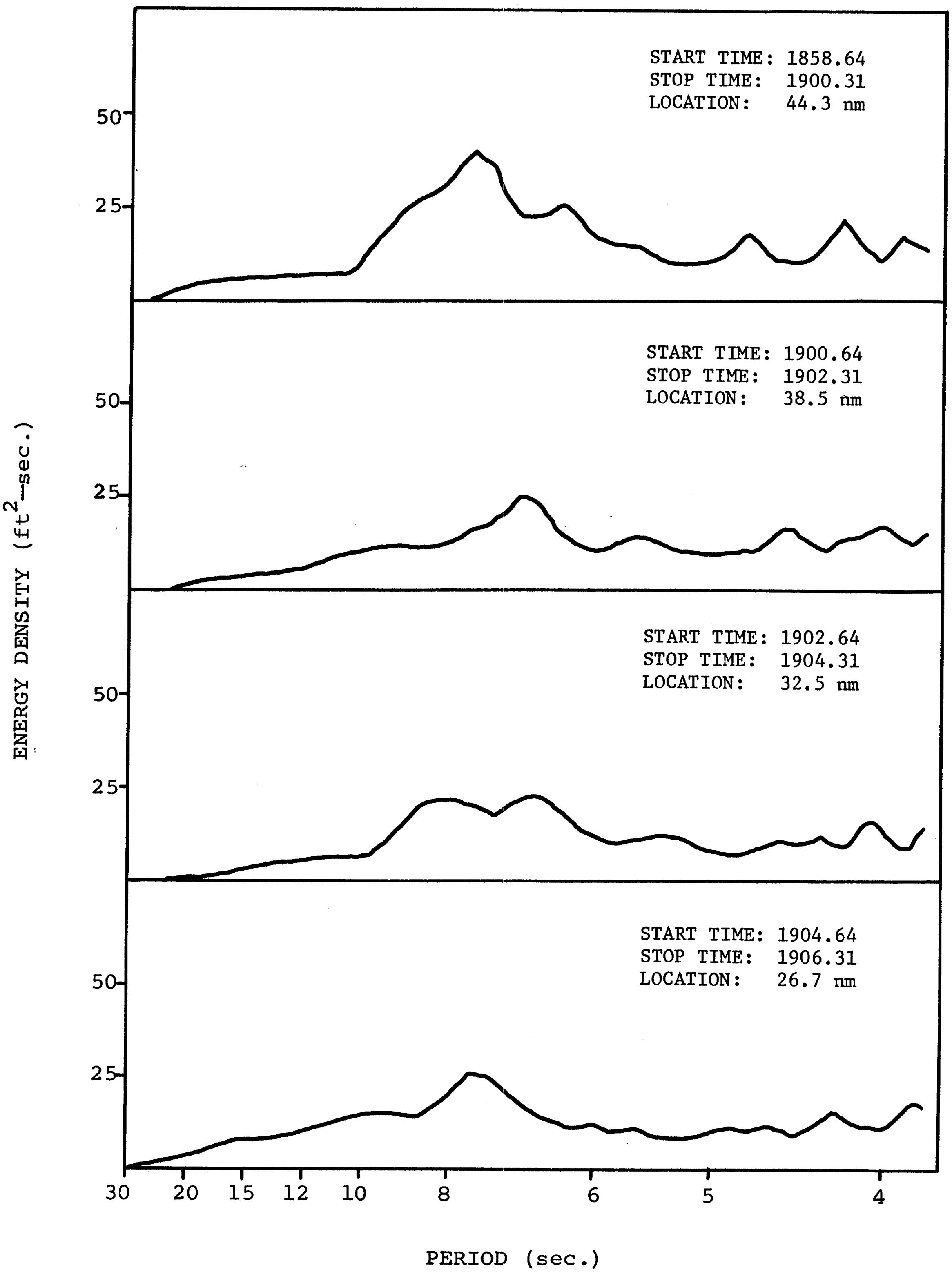

START TIME: 1858.64
STOP TIME: 1900.31
LOCATION: 44.3 nm
START TIME: 1900.64
STOP TIME: 1902.31
LOCATION: 38.5 nm
START TIME: 1902.64
STOP TIME: 1904.31
LOCATION: 32.5 nm
START TIME: 1904.64
STOP TIME: 1906.31
LOCATION: 26.7 nm
50
25
ENERGY DENSITY (ft^2—sec.)
30
20
15
12
10
8
6
5
4
PERIOD (sec.)

FIG. 22 (cont.).

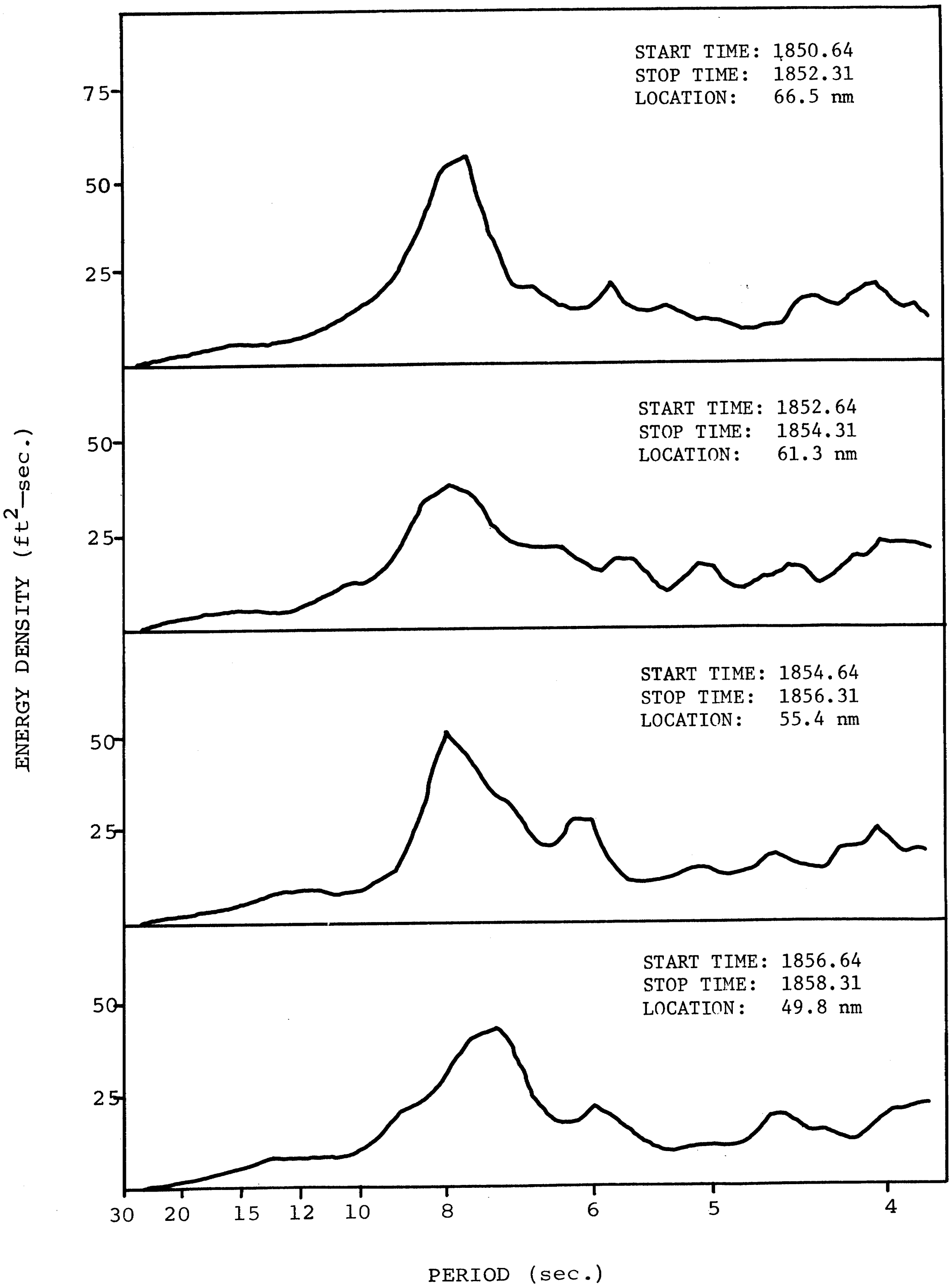
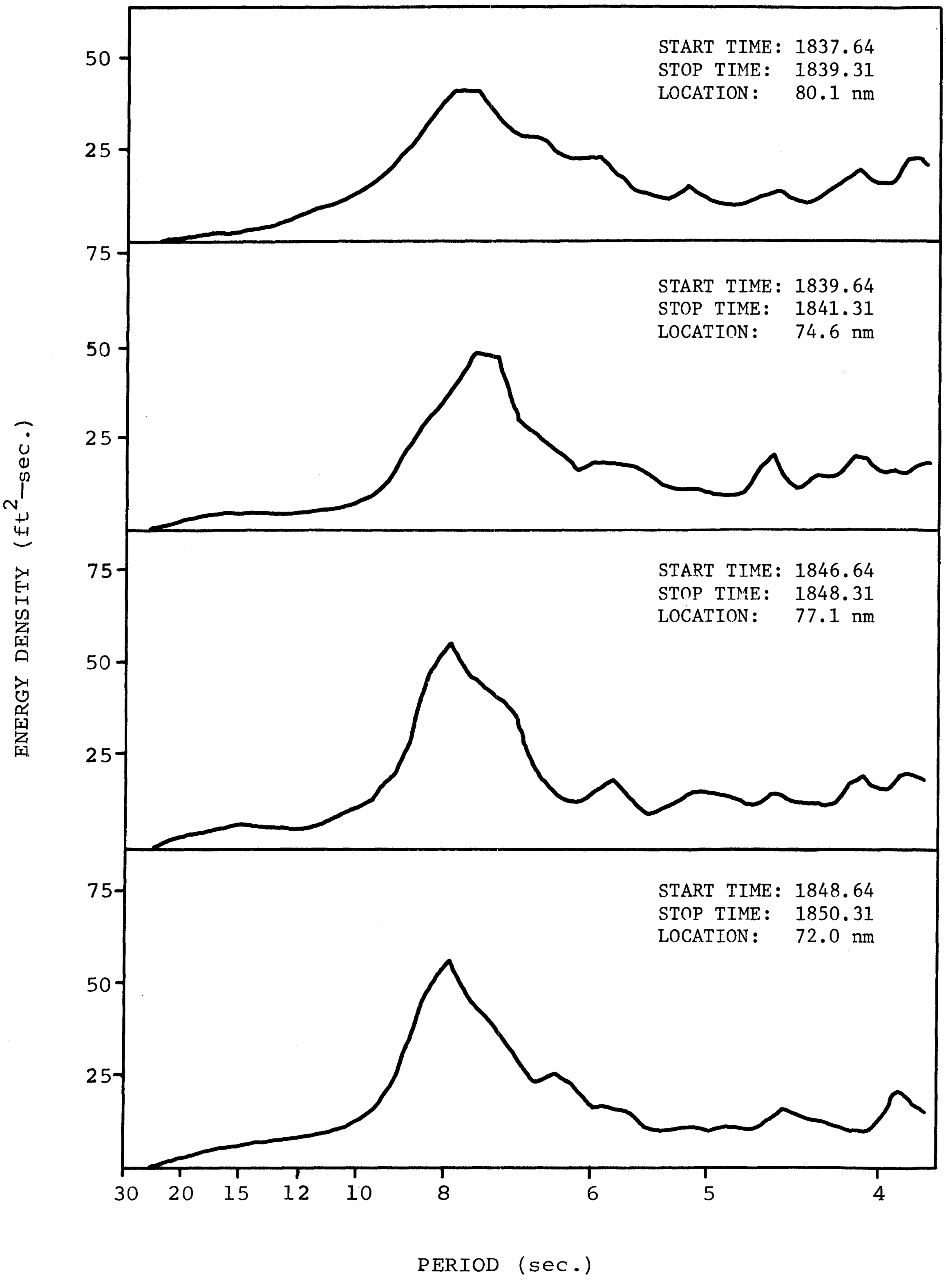

START TIME: 1850.64
STOP TIME: 1852.31
LOCATION: 66.5 nm
START TIME: 1852.64
STOP TIME: 1854.31
LOCATION: 61.3 nm
START TIME: 1854.64
STOP TIME: 1856.31
LOCATION: 55.4 nm
START TIME: 1856.64
STOP TIME: 1858.31
LOCATION: 49.8 nm
ENERGY DENSITY (ft^2—sec.)
75
50
25
30 20 15 12 10 8 6 5 4
PERIOD (sec.)

FIG. 22 (cont.).



START TIME: 1837.64
STOP TIME: 1839.31
LOCATION: 80.1 nm
START TIME: 1839.64
STOP TIME: 1841.31
LOCATION: 74.6 nm
START TIME: 1846.64
STOP TIME: 1848.31
LOCATION: 77.1 nm
START TIME: 1848.64
STOP TIME: 1850.31
LOCATION: 72.0 nm
ENERGY DENSITY (ft^2—sec.)
50
25
75
30
20
15
12
10
8
6
5
4
PERIOD (sec.)

FIG. 22 (cont.).

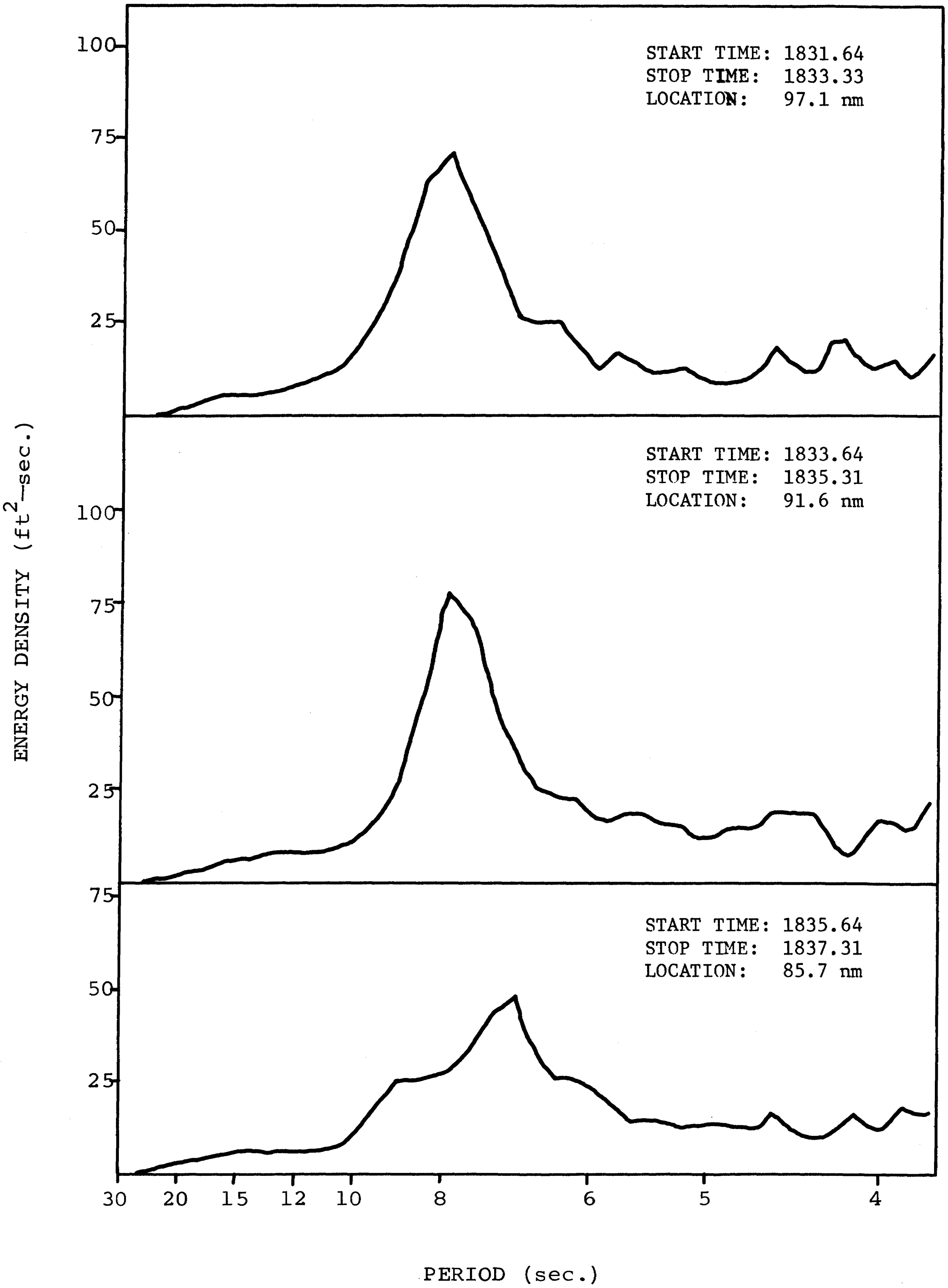
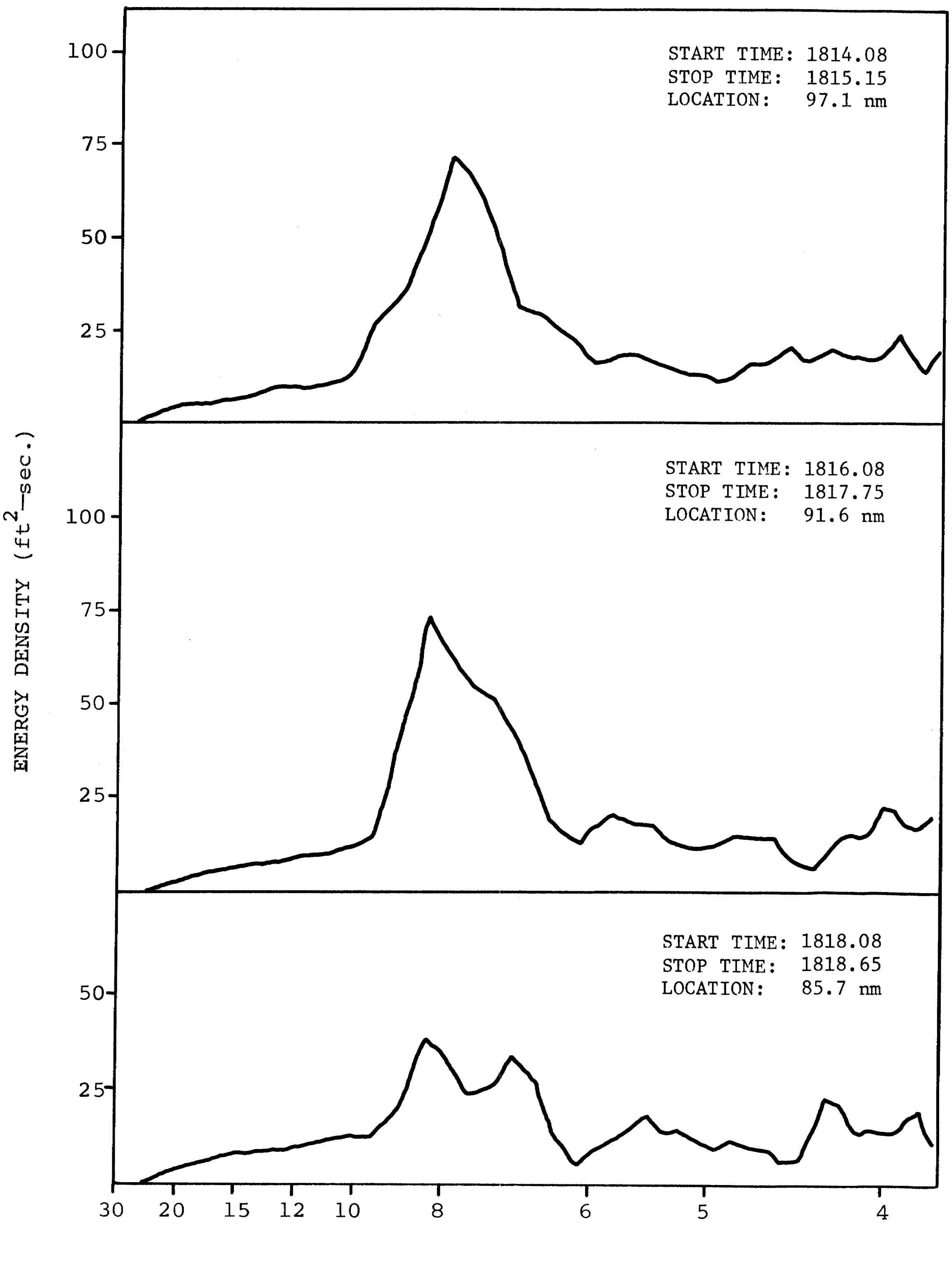

START TIME: 1831.64
STOP TIME: 1833.33
LOCATION: 97.1 nm
START TIME: 1833.64
STOP TIME: 1835.31
LOCATION: 91.6 nm
START TIME: 1835.64
STOP TIME: 1837.31
LOCATION: 85.7 nm
ENERGY DENSITY (ft^2—sec.)
100
75
50
25
30 20 15 12 10 8 6 5 4
PERIOD (sec.)

FIG. 22 (cont.).



START TIME: 1814.08
STOP TIME: 1815.15
LOCATION: 97.1 nm
START TIME: 1816.08
STOP TIME: 1817.75
LOCATION: 91.6 nm
START TIME: 1818.08
STOP TIME: 1818.65
LOCATION: 85.7 nm
100
75
50
25
ENERGY DENSITY (ft^2—sec.)
30
20
15
12
10
8
6
5
4
PERIOD (sec.)

FIG. 22 (cont.).

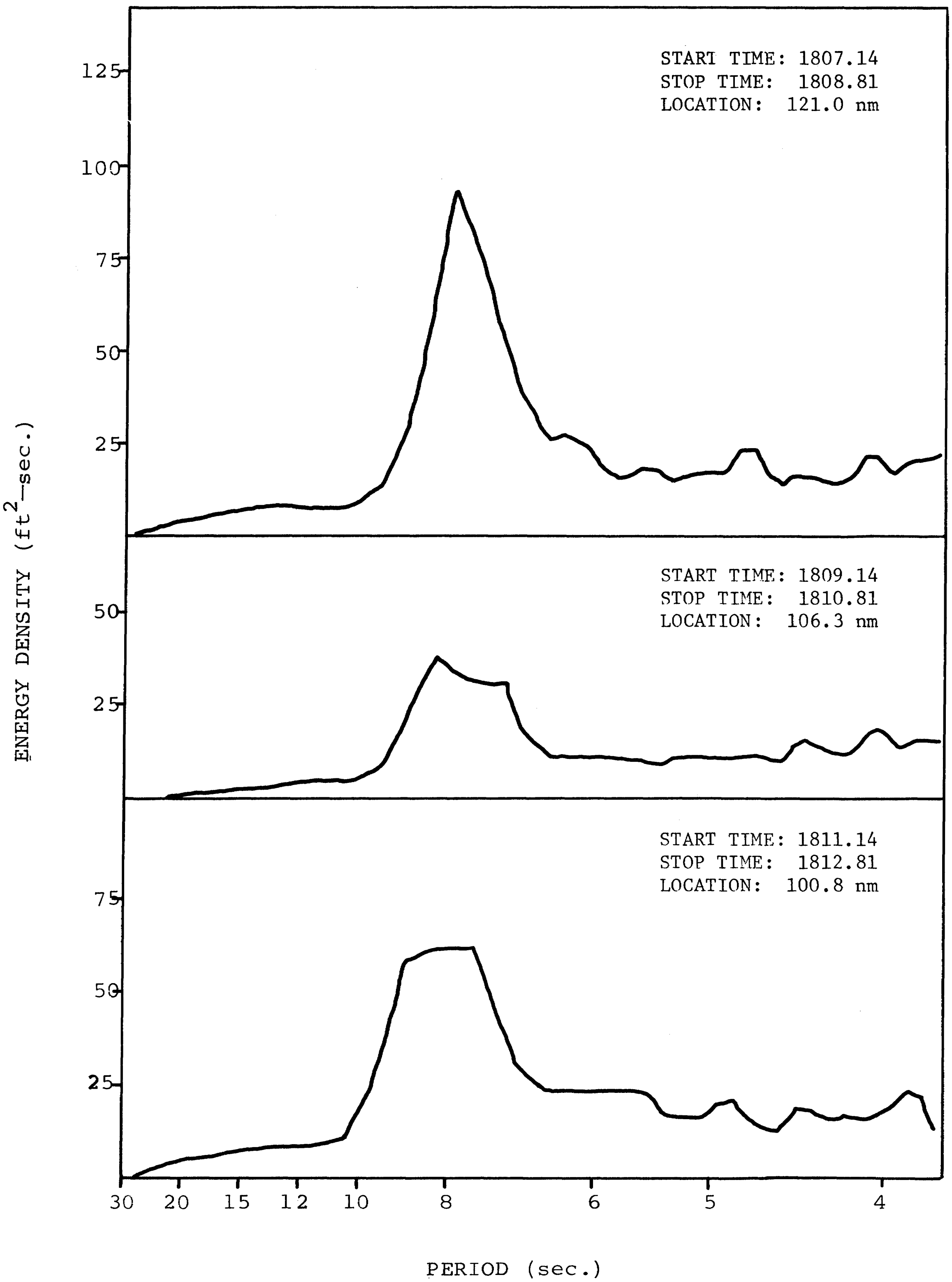

START TIME: 1807.14
STOP TIME: 1808.81
LOCATION: 121.0 nm
START TIME: 1809.14
STOP TIME: 1810.81
LOCATION: 106.3 nm
START TIME: 1811.14
STOP TIME: 1812.81
LOCATION: 100.8 nm
ENERGY DENSITY (ft²—sec.)
125
100
75
50
25
50
25
75
50
25
30 20 15 12 10 8 6 5 4
PERIOD (sec.)

FIG. 22 (cont.).

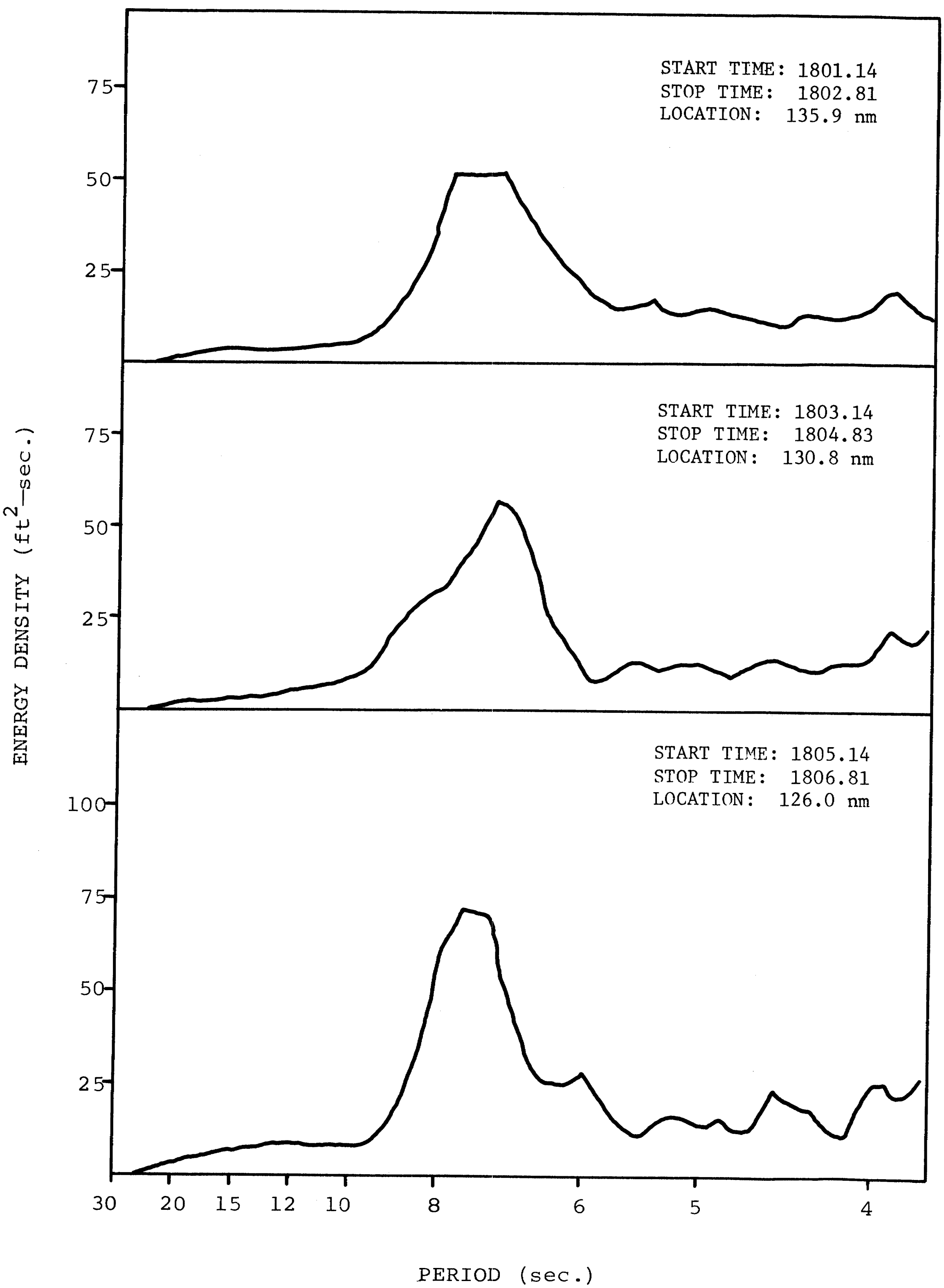

START TIME: 1801.14
STOP TIME: 1802.81
LOCATION: 135.9 nm
START TIME: 1803.14
STOP TIME: 1804.83
LOCATION: 130.8 nm
START TIME: 1805.14
STOP TIME: 1806.81
LOCATION: 126.0 nm
ENERGY DENSITY (ft^2—sec.)
75
50
25
100
30
20
15
12
10
8
6
5
4
PERIOD (sec.)

FIG. 22 (cont.).

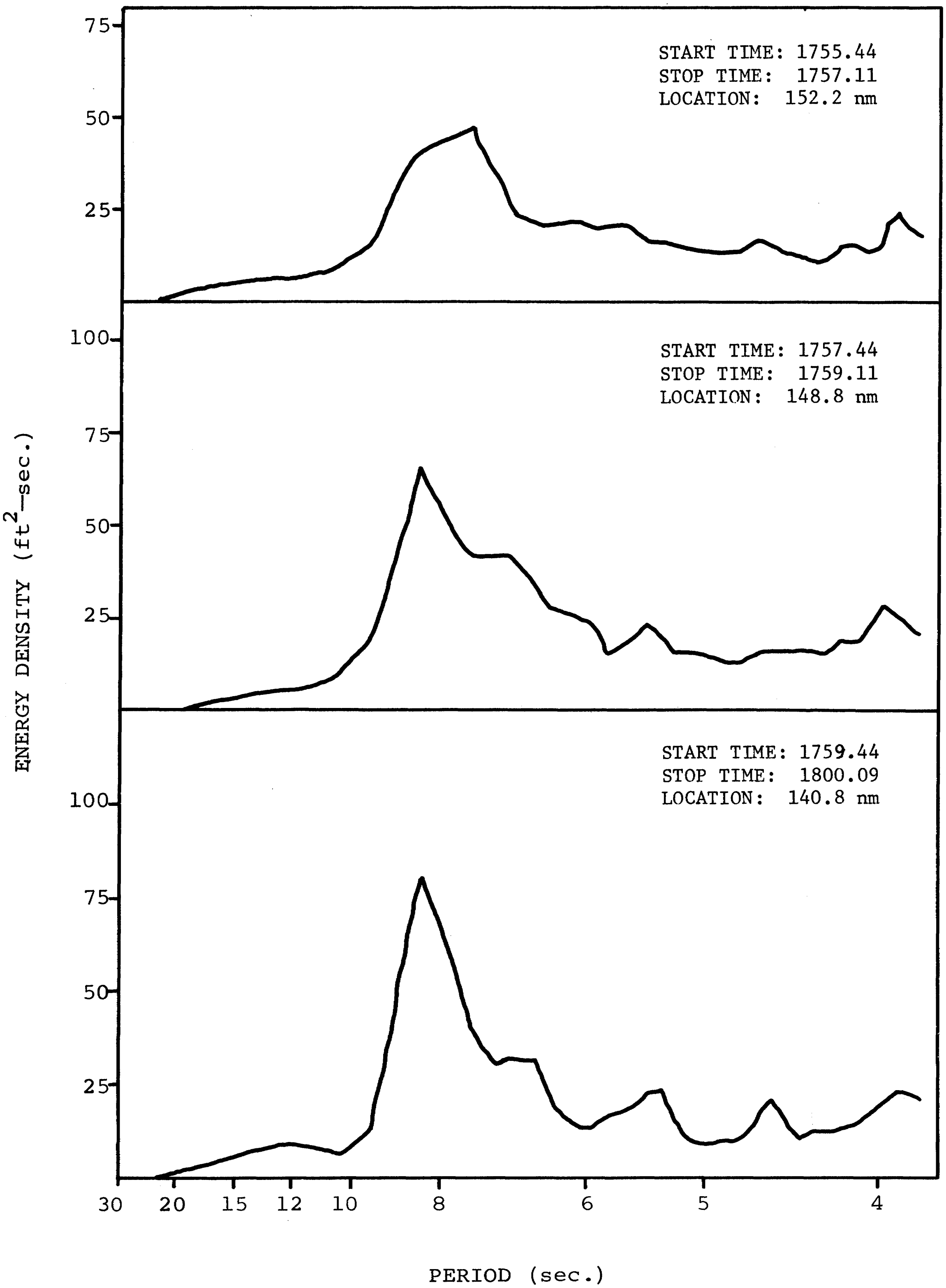
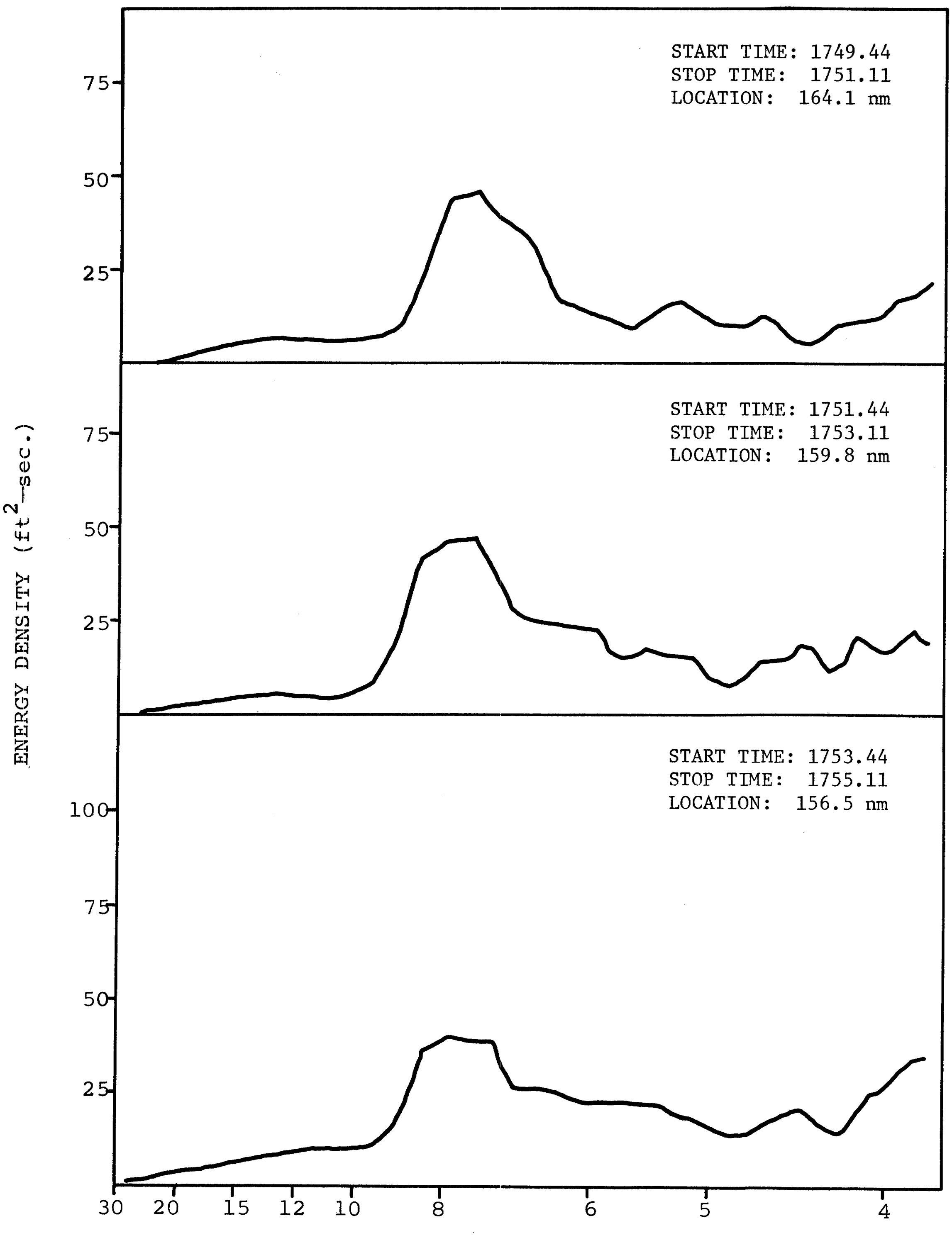

START TIME: 1755.44
STOP TIME: 1757.11
LOCATION: 152.2 nm
START TIME: 1757.44
STOP TIME: 1759.11
LOCATION: 148.8 nm
START TIME: 1759.44
STOP TIME: 1800.09
LOCATION: 140.8 nm
ENERGY DENSITY (ft^2-sec.)
75
50
25
100
75
50
25
100
75
50
25
30
20
15
12
10
8
6
5
4
PERIOD (sec.)

FIG. 22 (cont.).



START TIME: 1749.44
STOP TIME: 1751.11
LOCATION: 164.1 nm
START TIME: 1751.44
STOP TIME: 1753.11
LOCATION: 159.8 nm
START TIME: 1753.44
STOP TIME: 1755.11
LOCATION: 156.5 nm
ENERGY DENSITY (ft^2—sec.)
PERIOD (sec.)
75
50
25
100
30
20
15
12
10
8
6
5
4

FIG. 22 (cont.).

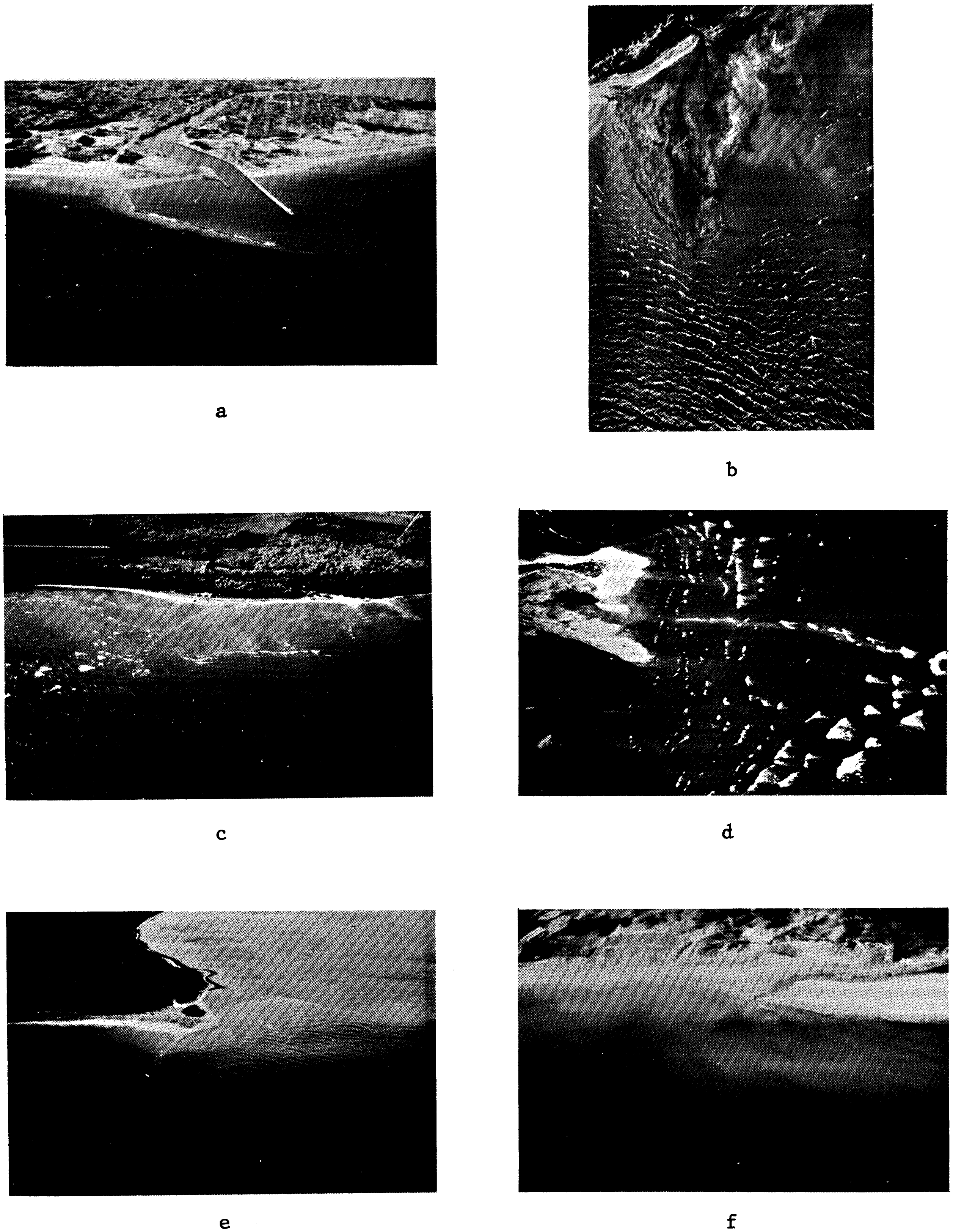


FIG. 23. Aero-Infrared Ektachrome photographs.

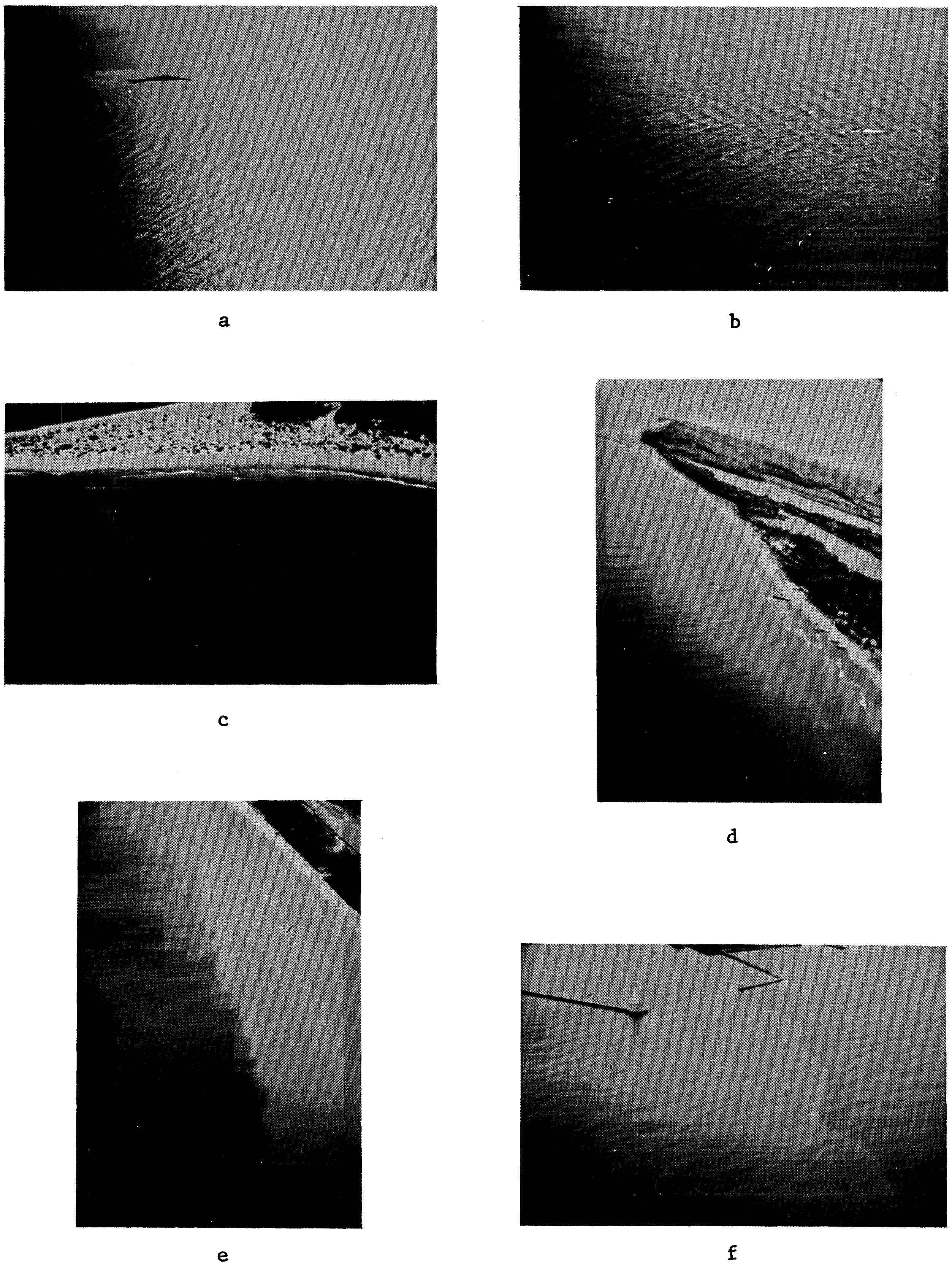


FIG. 24. Aero-Infrared Ektachrome photographs.